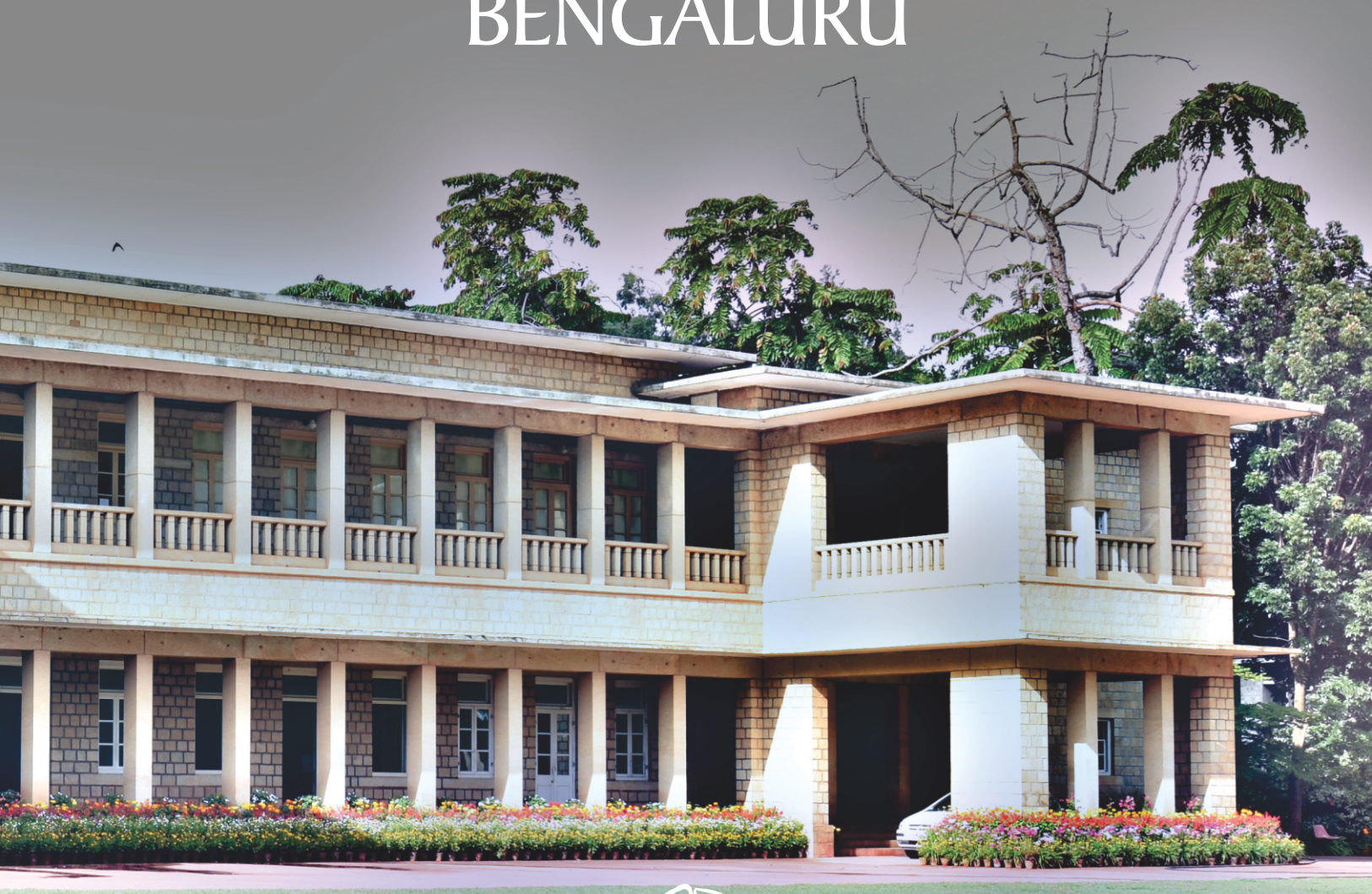
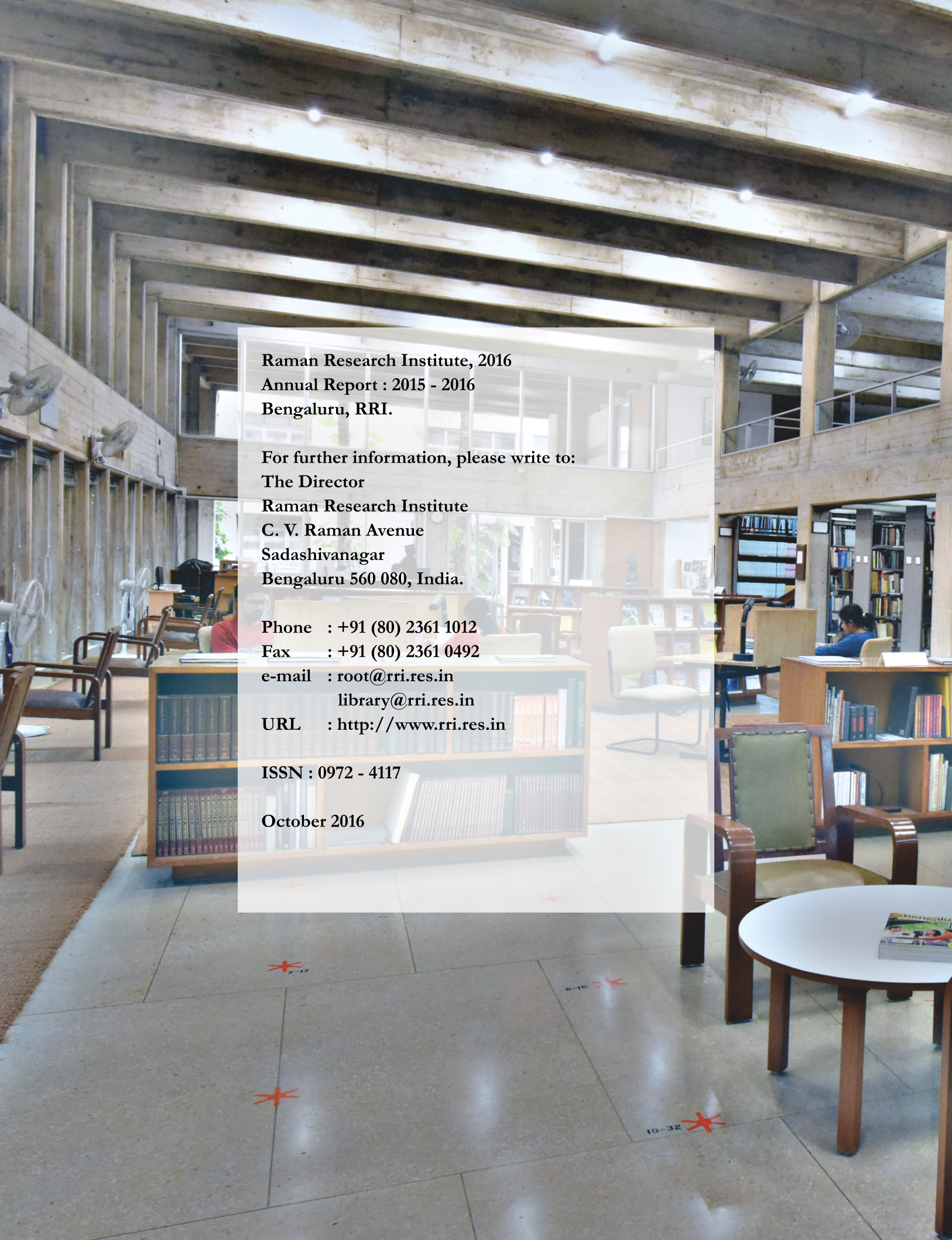
RAMAN RESEARCH INSTITUTE
BENGALURU





ANNUAL REPORT

2015 - 2016



Raman Research Institute, 2016
Annual Report : 2015 - 2016
Bengaluru, RRI.

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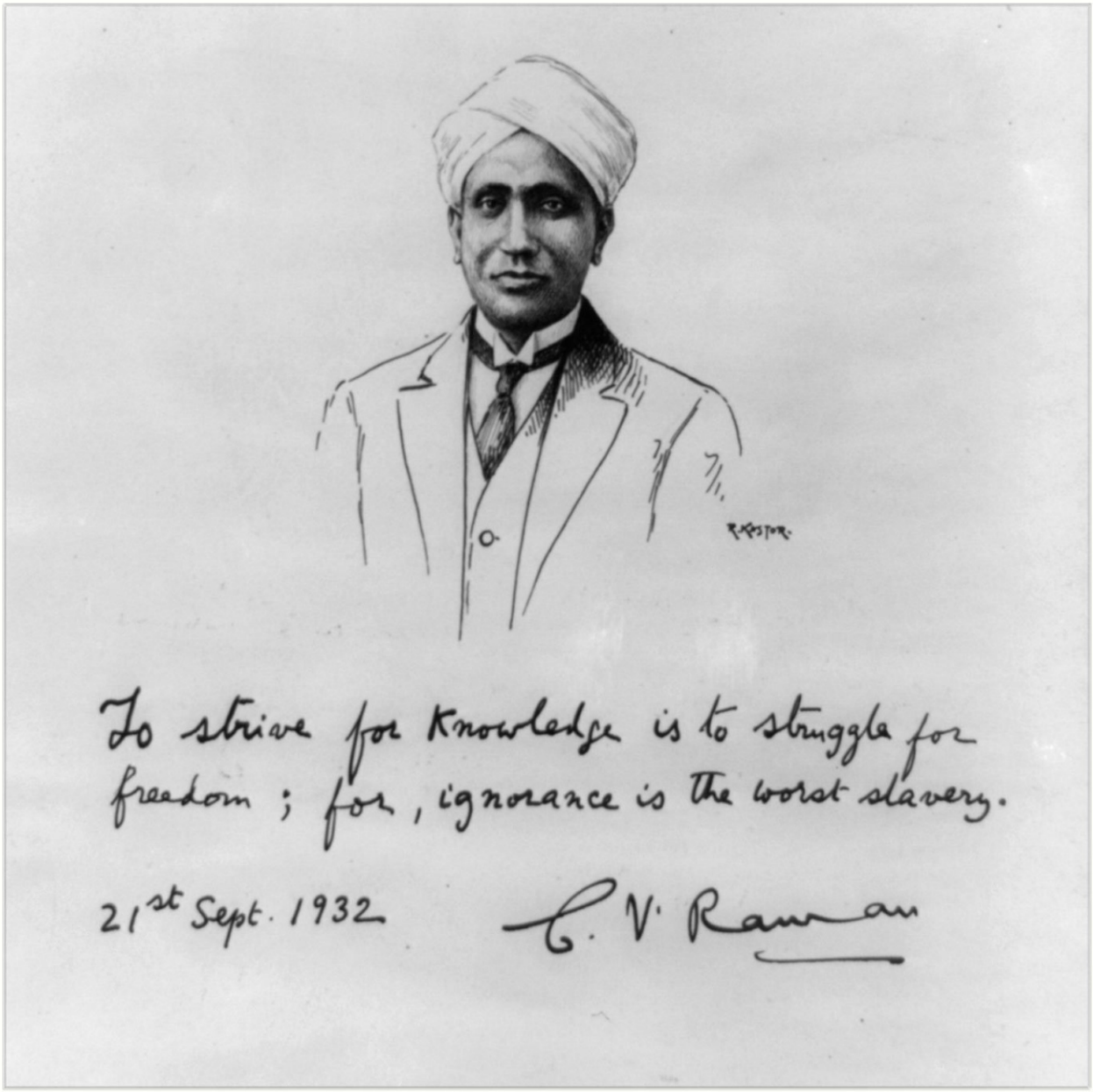
ANNUAL REPORT
2015 – 2016



Raman Research Institute

Bengaluru


VOLTAS



To strive for knowledge is to struggle for freedom ; for, ignorance is the worst slavery.

21st Sept. 1932 C. V. Raman

Sir C. V. Raman



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Director's Page



In August 2015 we were pleasantly surprised to hear that the Honourable Minister for Science & Technology and Earth Sciences, Dr Harsh Vardhan, had expressed a desire to come and spend a day with us.

The visit was a most enjoyable experience for all of us at the Institute. Dr Harsh Vardhan connected well with all of us – students and staff. As he entered different laboratories and met different groups across the scientific, technical and administrative staff, his informal approach put everyone at ease and the conversations were free flowing. He showed keen and genuine interest in understanding the goals of the research, appreciating the intents, and gently gave his perspective and suggested ways by which the paths might be nudged towards the greater goals that he and the Government envisioned.

The year saw RRI host several meetings on specialized topics of direct relevance to the research of the Institute, as well as empowering workshops, and also events that expand the horizons of the younger generation of which we have an ever-growing population. April 2015 saw a Cell Mechanics meeting on *Mechanical Manipulations and Responses on the Scale of Cells and Beyond*; June 2015 saw a meeting on *Cosmology with the 21-cm line*; July 2015 saw, once again, the annual *RRI School on Statistical Physics*, this time jointly hosted with ICTS-TIFR; July 2015 saw yet another event – a *Discussion Meeting on New Colloids*; Jan 2016 was time for a workshop at RRI on *Quantum Measure and Causal Set Theory*.

RRI had a role in the work leading to the launch of ASTROSAT, its successful first light in the many wavelength bands, and its establishment as an observatory of scientific value. RRI members played a significant role in pre-flight and in-orbit calibrations of the LAXPC payload, and a payload operations centre is functioning at RRI to enable science use of this instrument.

The year 2015-16 will be remembered for the first ever detection of gravitational waves. Following on from the expression of commitment to TMT and SKA, this year saw India join yet another mega-project in the field of astronomy – LIGO. And it is inspirational to reminisce the theoretical research of Professors Bala Iyer and C V Visweswara - who were staff at RRI - that

worthy LIGO discovery of gravitational waves, thus laying the foundations for meaningful participation of India in LIGO.

As a tribute and recognition of the almost decade of meticulous developmental effort towards making the first ever X-ray polarization measurements, ISRO has in the past year approved the POLIX polarimeter concept that was demonstrated in the RRI X-ray laboratory as the payload for a mission – XPoSat – to be launched in the coming years. Hard work is rewarded by demanding even more effort with tighter timelines!

RRI continues its involvement in the SKA – a megaproject of the nation – as a part of the SKA-India consortium. SKA is slated to be the world's largest and most sensitive radio telescope ever built. RRI is the only Indian Institution that has contributed to the International SKA Science Book, which defines the science goals of the SKA. And during the year gone by RRI continued its participation in science with precursor radio telescopes at the SKA site.

RRI, of course, is well aware of its indebtedness to society, the Department of Science and Technology, and the Government, for the excellent support that enables the free-spirited research that is often courageous and of high-risk type. RRI is distinctive and unique amongst peer research institutions in that several of its research themes have an emphasis on experimental efforts that necessarily require significant in-house technical proficiency and path-breaking advancements in experimental apparatus and methods, which often require years of perseverance and single-minded dedication. This is in continuation of the style of the Founder, Sir C V Raman, in a modern context.

The mandate of the Institute is to engage in research in basic science, with the aim of giving the country a respected standing amongst the international intelligentsia. The research conducted continually advances knowledge base in that the programmes result in improved understanding of the fundamental laws and behaviour of nature, laying the basic foundation for advancement of science and its consequent benefits to the society.

In recognition of the need for also engaging in ways to have a more direct impact, we open our doors to vast numbers of young students – via the extremely popular Visiting Students Programme and the Research Assistants programmes, apart from the regular PhD programmes. All these allow for a continuous flow of young minds through the campus, inspired towards research careers and empowered by the experience. And RRI scientific staff has gone out to engage with young minds in schools and universities – speaking basic science, speaking breakthrough science, mentoring students, and organizing workshops on topics as diverse as modern optics and modern telescopes.

Continuing on this theme, at RRI, the initiative to develop a Brain-Computer Interface saw the attainment of a milestone in the year gone by: the most recent development at this lab is of a visually activated control system that can be used in conjunction with a variety of devices (robotic arm, wheelchair, etc.) and a voice-controlled moving platform for use in wheel chairs, elevators etc. Separately, in another example of research of societal relevance, the Electrochemistry laboratory of RRI has invented an Impedance based `Hand held milk purity testing device' to detect the so-called `synthetic milk adulteration'; this work is the result of a joint collaboration with the DST-National Hub for Health care Instrumentation (NHHID) at Anna University, Chennai and Department of Electronics Systems and Engineering, IISc, Bangalore.

And in recognition of the need and obligation to connect and communicate our research to the public at large, we have now entered into an MOU with Gubbi Labs, specifically their Research Services Media Division, to communicate selected research and key events and achievements of the Institute to the public.

Ravi Subrahmanyan
17 August 2016

RRI at a Glance

RRI is an icon that symbolizes and represents the heritage of Indian physicist and Nobel Laureate Sir C V Raman, continuing his legacy and style of qualitatively impactful research that earns the nation a respectable place. The Institute preserves the inspirational spirit of this stalwart of our scientific cultural history.

History

Nobel Laureate, Sir C V Raman, founded the Raman Research Institute in 1948 on land that had been gifted to him by the Government of Mysore. After the Professor's demise in 1970, a public charitable trust was created - the Raman Research Institute Trust – and the lands, buildings, deposits, securities, bank deposits, moneys, laboratories, instruments, and all other movable and immovable properties were transferred to the RRI Trust. The function of the RRI Trust was to maintain, conduct and sustain the Raman Research Institute.

In 1972, the RRI was restructured to become an aided autonomous research institute and since then has been receiving funds for its research from the Department of Science and Technology of the Government of India. A set of Regulations and Bye-Laws were framed for its administration and management.

Administration

The Governing Council is the executive body of the Institute and conducts the administration and management of the Institute. The Director is the Chief Executive and Academic Officer and is responsible for the administration of the Institute. He exercises general supervision over the programmes and research projects of the institute. The Administrative Officer is responsible for the general administration of the Institute and represents it in legal and other related proceedings. The Finance Committee helps the Council with financial matters.

Mission

The mandate of the Institute is basic research with focus in niche fields of astronomy and astrophysics, quantum atom optics, quantum information, soft condensed matter and theoretical physics. The research activities include work in Chemistry, Liquid Crystals, Physics in Biology.

Director

The current director of the Raman Research Institute is Ravi Subrahmanyan.

Location

RRI is located on a 20-acre site in the north of Bangalore City, the IT capital of India. The brilliantly verdant campus provides a serene and soothing environment away from the hustle and bustle of the busy metropolis outside, perfectly suited for the creative research work being conducted within its confines.

Research Areas

Astronomy and Astrophysics
Light and Matter Physics
Soft Condensed Matter
Theoretical Physics

Research Laboratories

- X-ray Astronomy Laboratory
- Molecular Astronomy Laboratory
- Cosmological Recombination & Reionization Laboratory
- Sky Watch Array Network
- Light-Matter Interactions
- Laser Cooling & Quantum Optics
- Ultrafast and Onlinear Optics
- Quantum Information & Computing
- Quantum Interactions

Research Laboratories (Contd.)

- Phase Transitions & Electro-optics
- Rheology and Light Scattering
- Microscopy and Scattering
- Biophysics
- Chemistry
- Electrochemistry and Surface Science
- Liquid Crystal Display
- Microscopy and Dielectric Spectroscopy
- Nanoscale Physics of Soft and Living Matter
- Brain Computer Interface

Facilities

1. Laboratories:

- Analytical Physical Measurement Lab
- X-ray Diffraction Lab
- SEM Lab
- AFM Lab
- NMR Lab
- Micro-Raman Spectroscopy Lab
- Magnetic Studies Lab
- Photophysical Studies Lab

2. Mechanical Engineering

- Mechanical Workshop
- Sheet metal, paint and carpentry facility

3. Electronics Engineering

4. Library

5. Computer Facility

Education

RRI offers the following academic programmes:

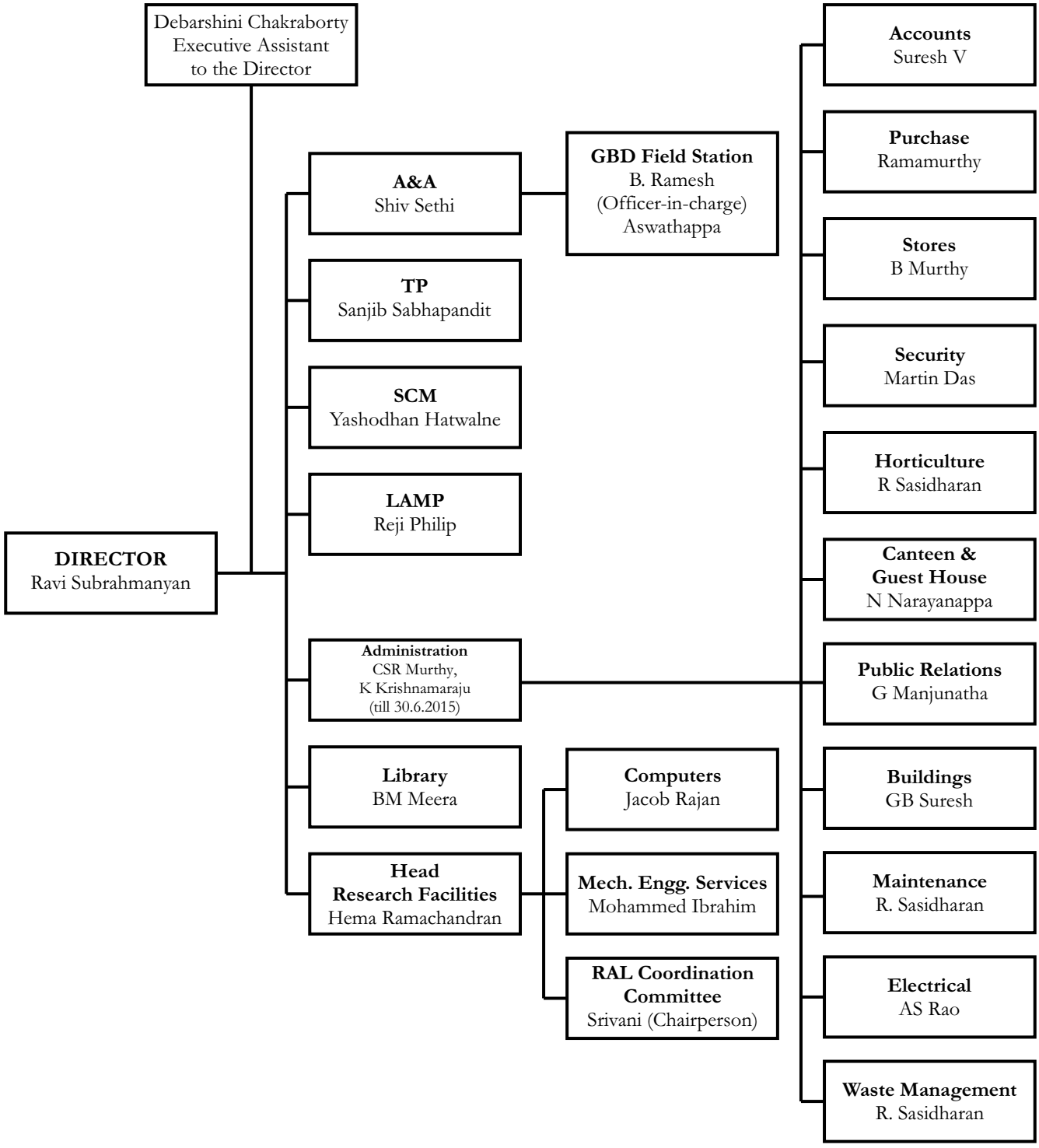
- PhD programme
- Postdoctoral Fellowship
- Pancharatnam Fellowships
- Visiting Students Programme

Funding

The research of the Institute is nurtured and sustained by grants-in-aid from the Department of Science and Technology, Government of India.

RAMAN RESEARCH INSTITUTE

CV Raman Avenue, Sadashivanagar
Bengaluru 560 080



Organisation

RRI Science Forum	:	Gautam Soni, Andal Narayanan, Nayantara Gupta
Colloquia	:	Joseph Samuel, Pramod Pullarkat, Sadiq Rangwala, Urbasi Sinha, V Lakshminarayanan
Hostel Wardens	:	Shiv Sethi, Arun Roy, B Ramesh, Urbasi Sinha
Admissions Coordinator	:	Ranjini Bandyopadhyay
SAAC Pullarkat, Shiv Sethi	:	VA Raghunathan (Chairperson), Sadiq Rangwala, Sumati Surya, Pramod
In-House meeting	:	PhD students – 3rd year
JAP Rep of RRI	:	S Sridhar
Complaints Committee	:	Srivani (Chairperson), BM Meera, CSR Murthy, Madan Rao, Mamatha Bai
Overseas Travel Commitee	:	Biswajit Paul (Chairperson), Madan Rao, Reji Philip
Evaluation Committee	:	KS Dwarakanath (Chairperson), Joseph Samuel, Biman Nath, VA Raghunathan, Sadiq Rangwala
Academics & Research Committee	:	Joseph Samuel (Chairperson), Hema Ramachandran, Biman Nath
Coordinator of Visiting Students Programme	:	Andal Narayanan
Library	:	BM Meera (Chairperson), Yashodhan Hatwalne, Supurna Sinha, Reji Philip, Nayantara Gupta
RRI Official Language & Implementation Committe	:	CSR Murthy (Chairperson), Suresh Varadarajan, Ranjeet Koshta, R Ramesh, CN Ramamurthy, B Srinivasamurthy, BM Meera, G Manjunatha, K. Radhakrishna, V Vidyamani, Harini Kumari, Mamatha Bai, Jacob Rajan

Prelude

RRI is an icon that symbolizes and represents the heritage of Indian physicist and Nobel Laureate Sir C V Raman, continuing his legacy and style of qualitatively impactful research that earns the nation a respectable place. The Institute preserves the inspirational spirit of this stalwart of our scientific cultural history.

Historically, our pioneering experimental work in Liquid Crystals has earned us international recognition for the invention of Discotic Liquid Crystals, which is the material that enables wide viewing in television and other display screens world wide. Today, research at the Raman Research Institute focuses primarily on the following areas in basic science - Astronomy and Astrophysics, Light and Matter physics, Soft Condensed Matter physics, and Theoretical Physics. The research activities also include Chemistry, Liquid Crystals, Physics in Biology, Quantum information, Quantum communications and Signal Processing, Imaging & Instrumentation.

The Institute has played significant enabling role in making India's presence in International science megaprojects. Professors Bala Iyer and C V Visweswara, who were research staff at RRI, did foundational research leading to the recent Nobel-prize worthy LIGO discovery of gravitational waves; RRI thus laid the foundations for India participation in LIGO, which is now a megaproject of the nation.

RRI is now a partner with MIT, Harvard in the US, and universities and CSIRO in Australia, and New Zealand, and we have together built in the remote outback of Western Australia the Murchison Wide-field Array (MWA) Radio Telescope – a precursor to the International Square Kilometre Array Radio Telescope (SKA), which is another megaproject of the nation. RRI contribution was in the hardware design and Making-in-India the high-technology digital receivers, which our engineers and scientists did in-house at RRI and with help of industry in Bangalore. Today the telescope is fully functional in the Western Australian desert, has been extremely productive in its research, and RRI is part of every publication. RRI is part of the collaborative key SKA science goal of discovering the formation of the first stars and galaxies in the Universe, and RRI is the only Indian institute that has contributed to the SKA Science defining book.

RRI is engaged in Making-In-India high technology radio-astronomy radiometers to lead the world in discovery of the formation of first atoms, stars and galaxies in the universe, a Nobel-prize worthy research. RRI scientists and engineers have built prototypes and tested these in remote and high-altitude Hanle observatory in Ladakh, where we fortunately have one of the best astronomical observing sites in the world. A cluster of these compact radiometers may be interspersed amongst the antennas of the International SKA radio telescope antennas, to enable and lead SKA research into the Key Science of Cosmic Dawn and the formation of first stars and galaxies in the Universe. These outrigger precision radiometers are proposed to form an identifiable hardware with a unique research goal that would be specifically recognized as an Indian accomplishment and contribution to the megaproject.

Members of the Astronomy & Astrophysics group at RRI have proposed two new optical designs for radio telescopes that use a Fan Beam Telescope (FBT) as a component. Currently, RRI is engaged in building a Fan Beam Telescope - Low Frequency (FBT-LF) with the purpose of demonstrating its functioning and the expected benefits of the new designs.

Alongside, to simultaneously engender manpower growth in the country towards ensuring substantial participation in the SKA megaproject in the coming decades, RRI has embarked on the SWAN project – Sky Watch Array Network - to fan out antenna arrays across universities in India that would initiate and enthuse younger minds into technology and science of radio astronomy via their participation in a networked project that explores the emerging field of time-domain astronomy and advanced signal processing.

RRI thus ensures India's meaningful and respectable participation in the SKA megaproject by contributing to the SKA Science definitions, bidding to design and build in India precision radiometers to enable and extend SKA capability in its key science, while simultaneously growing a cohesive younger generation that will continue the country's leadership in this futuristic international research.

In the area of X-ray astronomy, RRI is currently Making-in-India an Indian X-ray polarimeter (POLIX), as a payload for a dedicated small satellite mission of ISRO called XPoSat. POLIX will open a new window in high energy astrophysics. POLIX is poised to be the first X-ray polarimeter mission in the world, to measure X-ray polarisation of cosmic X-ray sources, ahead of NASA and ESA space missions.

Researchers at RRI have done experiments that improve our understanding of the physical properties of the plasma membrane of nerve cells or axons using a novel laser-based force measurement technique developed and Made-in-India at RRI. They have thus established the response of nerve cells to mechanical and chemical stress, leading to better understanding of neurodegenerative mechanisms and possible strategies for axonal loss. Axonal plasticity and maintaining uniform axonal diameter for a neuron are vital to preventing this mechanical axonal loss that is the main reason for onset of neurodegenerative diseases. This research could lead to better and more optimal drugs to counteract any disruption of the above in the brain. Another topic of definite biomedical interest is the research done on drug delivery through specially designed vehicles called 'micelles', where the rupture of the micelle can release the drug depending upon the pH of the solution, temperature and drug chemistry. This is a study that can lead to technology towards targeted, or so-called smart, drug delivery.

The RRI cluster of Quantum optics laboratories are now established as a leading center for cold-atom and quantum information research in the country, training a large number of PhD and visiting students in this emerging field that also involves quantum physics in communications and computing. Recently, the Weapons and Electronics Systems Engineering Establishment (WESEE) which is the research division of the Indian Navy, DEiTY (Department of Electronics and Information Technology) and ISRO have expressed interest and 'in principle' support for a secure quantum communication project that is satellite based and uses 'Quantum key distribution' as its working principle. The quantum atom optics, quantum information and computing cluster of laboratories has established itself over a decade as a leading centre in the country for experimental quantum physics, and is hence uniquely poised to take on the key task of providing secure communications for the nation via development of the technology for quantum key distribution using entangled photons. No other Indian institution has the track record or proficiency in quantum communications to take the lead towards establishing for India a secure quantum communications. The QuaInt lab has succeeded in the creation of ultra-cold molecules and molecular ions in hybrid ion-atom-molecule and photon trap experiments. The novelty of the hybrid trap created by this group is that the number of trapped species and their internal states are precisely controlled and their long survival times have permitted the study of interactions between the species with unprecedented accuracy, thus improving our understanding of the quantum physics in the atomic systems. The group has also successfully designed an All-Optical-Switch (AOS) where switching light with light has been demonstrated and the phenomenon has been provided with a theoretical model. Such an AOS is a key component for any computing architecture that uses photons and thus has many practical applications. These fundamental researches that are important for the standing of the nation in the international scientific world, and for development of key enabling technologies in quantum systems, are possible exclusively at RRI.

A fundamental contribution to human knowledge by the Theoretical Physics group of RRI is the derivation of a fundamental quantum limit on the measurement of time in a gravitational field. The research showed that gravity and quantum mechanics set a fundamental limit on the fractional frequency uncertainty of clocks. This means there is a cap on the physically achievable accuracy of the atomic clocks being devised for better satellite communication, GPS, space navigation, etc.

Since the days of the Founder, Sir C V Raman, the Institute has engaged in experimental research of a rare kind. We selectively target a few unsolved questions in basic science that require purposeful technological innovation – a building of apparatus in Soft Matter, Quantum Atom Optics and Information, Astronomy, and Biophysics, which cannot be bought off the shelf and instead requires design, building, calibration, commissioning, mathematical inference to derive the physics and astrophysics. RRI is distinctive and unique amongst peer research institutions in that several of its research themes have an emphasis on experimental efforts that necessarily require significant in-house technical proficiency and path-breaking advancements in experimental apparatus and methods, which often require years of perseverance and single-minded dedication. This is in continuation of the style of the Founder, Sir C V Raman, in a modern context.

RRI is well aware of its indebtedness to society, the Department of Science and Technology, and the Government, for the excellent support. The mandate of the Institute is to engage in research in basic science, with the aim of giving the country a respected standing amongst the international intelligentsia. The research conducted continually advances knowledge base in that the programmes result in improved understanding of the fundamental laws and behaviour of nature. This is the seed that eventuates in all innovations that improve the quality of life for humankind, including that of people in rural areas of the country.

RRI has an initiative, of direct societal relevance, to develop a Brain-Computer Interface. The most recent development at this lab is of a visually activated control system that can be used in conjunction with a variety of devices (robotic arm, wheelchair, etc.) and a voice-controlled moving platform for use in wheel chairs, elevators etc. Separately, in another example of research of societal relevance, the Electrochemistry laboratory of RRI has invented an Impedance based `Hand held milk purity testing device' to detect the so-called `synthetic milk adulteration'.

In recognition of the need for also engaging in ways to have a more direct and long lasting impact, the institute open its doors to vast numbers of young students. The research programmes involve knowledge transmission via PhD students, young Research Assistants, and the Visiting Students, thus generating and empowering manpower with higher education, learning and advanced skills. RRI runs a highly successful internship programme called the 'Visiting Students Programme'. It is meant for undergraduate students or those pursuing their Masters degrees or is in a gap year within a year of completion of their degrees. The program empowers and motivates students across disciplines with experience of basic science research – both theoretical and experimental.

All these allow for a continuous flow of young minds through the campus, inspired towards research careers and empowered by the experience. And RRI scientific staff have gone out to engage with young minds in schools and universities – speaking basic science, speaking breakthrough science, mentoring students, and organizing workshops on topics as diverse as modern optics and modern telescopes.

ASTROPHYSICS AND ASTRONOMY

There are broadly three aspects to the research of the Astronomy & Astrophysics group – (a) Theoretical Astrophysics that involves development of analytical models and computational numerical simulations describing the dynamics, physical properties and underlying phenomena in celestial objects like stars, planets, galaxies, interstellar medium etc. Theorists also work on answering fundamental questions on the formation and evolution of the Universe, a branch of astrophysics called cosmology. (b) Observational astronomers on the other hand use telescopes built across the globe to study radiation from space across the entire electromagnetic spectrum – low frequency (long wavelength) radio waves to very high frequency (short wavelength and highly energetic) gamma rays. These observations test existing theoretical models and also give rise to new questions that call for answers. (c) The third aspect involves the design, construction and operation of telescopes, which are often built for very specific purposes, and are strategically located around the world and in space. RRI has an Astronomy & Astrophysics group that embraces research work in all these three facets.

RESEARCH AREAS

THEORETICAL ASTROPHYSICS

Cosmology

Cosmology is the study of our Universe as a whole – including the dynamical and astrophysical evolution from the Early Universe to its present form. A recent result in this field is that most of the neutral hydrogen in the redshift range 1.18-1.34 is not contained in star-forming galaxies but instead remains concentrated in smaller galaxies. This has implications in understanding the composition and source of neutral hydrogen in star-forming galaxies at redshifts close to 1.3. Other questions being addressed in this field include a study of the impact of alternate models of dark matter on HI distribution at high redshifts and the applicability of 2p-2s masers as a probe for primordial black holes. This year, data from the Murchison Widefield Array have also been analysed for detection of redshifted 21-cm from the Epoch of Reionization (EoR) and a new pipeline to analyse 3 hours

of raw data collected using both tracking and drift scan strategy has been formulated.

Cosmic Rays, Gamma Rays and Neutrinos

Highly energetic particles (protons, nuclei, photons and neutrinos) detected on Earth get accelerated in galactic and extragalactic environments. Theoretical modelling of the origin, production and propagation of these high-energy particles is used to interpret observations from gamma ray detectors, such as Fermi LAT, HESS, MAGIC, AGILE and the Ice Cube neutrino telescope. These models are then applied in understanding galactic sources, extragalactic sources like gamma ray bursts, and the emission mechanisms and environment in quasars associated with active galactic nuclei. During the period 2015-16, research has been conducted on multi-wavelength emission associated with highly energetic particles in blazars and quasars, with an aim to understand the underlying acceleration mechanisms of such particles in jets. Last year, studies on the proton synchrotron radiation from extended jets of PKS 0637-752 and 3C 273 have been performed. Other intriguing questions in this field being investigated currently include the properties of high-energy neutrinos from the now-famous gravitational wave event GW150914 that could possibly be associated with a short gamma-ray burst detected by the Fermi Gamma-ray Burst Monitor (GBM) 0.4 s after the GW event and within localization uncertainty of the GW event.

Galaxies and their Surroundings

The interaction between galaxies and their surroundings plays an important role in the evolution of galaxies and the intergalactic medium. The interactions involve the flow of gas acted upon by radiation pressure, cosmic rays and the galaxy's gravitational field. These complex processes are studied using both analytical methods and hydrodynamic simulations. Of interest are violent gaseous outflows from galaxies. Recent research in this area is addressing problems such as the Fermi bubble or the intensely bright gamma-ray feature rising from the centre of the Milky Way that also happens to be rich in X-rays and microwave emission; suppression of galactic outflows by the hot circumgalactic gas in galaxies; merger of supernovae in massive star clusters to form super bubbles; diffuse X-ray emission from galaxies with its root, once again, in the hot circumgalactic gas and exploration of possible signatures of the circumgalactic medium in the CMB through cross-correlation analyses.

Stellar Dynamics in Galactic Nuclei

The nuclei of galaxies have dense clusters of stars orbiting super massive black holes (BH); two nearby examples are the Galactic centre and the nucleus of the Andromeda galaxy. Gravitational force between the bodies mainly governs the structure, dynamics and evolution of the stellar system. Both dynamical and statistical mechanical methods are being used to formulate a theory of the long-term evolution of these Keplerian stellar systems with long-range interactions. Phenomena studied include collisionless dynamics of the star-cluster, instabilities, relaxation to equilibrium and fuelling of the BH, which contributes to its mass and spin.

Explanatory Dynamics

Most explanatory systems in binary stars consist of one or more planets orbiting a primary star with a wide binary stellar companion. The planetary eccentricities and mutual inclinations can be large, and may be due to gravitational forcing by the binary companion star. However, the role of a wide binary star on planetary evolution had until now remained largely unexplored. During 2015-16, work has been done in RRI on presenting a mechanism that has the potential to explain several observed features of explanatory statistics especially in binary stars with a single planet system. The work also seeks to explain the whys and how of the discernibly lower number of binary stars with multi-planet systems.

OBSERVATIONAL ASTRONOMY

Diffuse Radio Emission from Galaxy Clusters

Galaxy clusters are some of the largest gravitationally bound structures in the Universe. As many as hundreds of galaxies can be bound in a volume with linear extents of a few million light years. The space between the galaxies, the Intra Cluster Medium (ICM), is often home to sources of bright diffuse radio emission. This radio emission is known to be of non-thermal origin and is due to relativistic electrons radiating in the cluster magnetic field. Observations and interpretations of the origin of diffuse radio emission from galaxy clusters has implications on the understanding of large scale magnetic

fields in clusters, cluster mergers, and cluster evolution. These observations are being carried out using a variety of radio telescopes like the Giant Meterwave Radio Telescope (GMRT), the Very Large Array and the Murchison Widefield Array, which was built by RRI and international partners in a collaborative project. During the period 2015-16, Murchison Widefield Array observations of the galaxy cluster, Abell 3667 have been analysed by the A&A group at RRI. Talking about the ICM also leads us to the detailed study on the Arp 65 interaction debris that was concluded this past year. These debris results from pre-merger tidal interactions between pairs of galaxies. Separately, using data from GMRT and Chandra X-ray data, six massive star clusters are also being investigated with an aim to demystify their diffuse radio and X-ray emission.

Pulsars

Pulsars are rapidly spinning high-magnetic-field neutron stars that originate in supernovae. These were originally discovered in their pulsed radio emission; however, today they have been detected in pulsed emission across the electromagnetic spectrum. Pulsar emissions provide information about their structure, the high-energy processes in the magnetosphere, and their interactions with their environment and can also be used as a test platform for General Relativity. Millisecond pulsars are one of the most accurate clocks in the Universe. RRI conducts active research on pulsars and develops radio receivers and X-ray detectors that can help us understand their nature. Comprehensive studies on timing and spectral characterisation, pulse profile evolution and the pulsar spectrum of emitted X-rays are being conducted on pulsars of various types. Other studies like periodicity determination from a sequence of occasional single pulses**,** detection methods of off-pulse radio emission from pulsars vis-à-vis their reliability; along with searches for fast radio bursts (FRBs) too are underway.

Radio Galaxy Morphologies

Amongst the population of many different types of radio galaxies it is the X-shaped radio galaxy in particular, with its two typical lobes accompanied by two others, which together give the source a shape like the letter X that is currently being investigated by some members of the Astronomy group at RRI. How the two additional lobes are generated is debatable and is of importance to understand the coalescence of supermassive black holes and generation of gravitational wave background. In the X-shaped radio galaxy, two lobes appear to be active while the other two are relics or spillovers of plasma from the main axis. Research is on at RRI to test various existing theories on the shape and structure of X-shaped radio galaxies. During the period 2015-16 total intensity and polarization data from 56 radio sources out of a whole sample of 99 radio sources have been observed using the JVLA telescope. Searches for cores and jets that can possibly help decipher the origin of large scale X-shaped radio structures also continue.

With the availability of low frequency images of the southern sky mapped with the Murchison Wide-field Array (MWA) a comparative study of radio source structures at low frequencies against their counterparts in images obtained at high frequencies is being performed in order to know more about the true extent of radio sources, and/or the presence of relic radio emission in these sources.

X-Ray Binaries

Compact stars (neutron stars and black holes) create some of the most extreme conditions in the universe. Their high-energy emission, mostly X-rays, can be accessed using space X-ray observatories. Astronomers at RRI use observations made using a range of international space observatories to investigate X-ray binary properties such as self absorption in X-ray pulsars and dips in their pulse profiles, cyclotron absorption lines in X-ray pulsars, and variations in intensity and pulsation characteristics during eclipse/partial eclipses among others. The Indian multi-wavelength astronomy satellite ASTROSAT and an Indian X-ray polarimeter POLIX that is being built at the Raman Research Institute will enhance X-ray binary research at RRI substantially.

RADIO TELESCOPES AND ASTRONOMY

Members of the Astronomy & Astrophysics group along with the Radio Astronomy Laboratory of the Institute are involved in projects concerning various telescopes throughout the world. Questions like radio signatures from the Epoch of Reionization and transient radio phenomena, particularly fast radio transients, have shaped the design of next generation radio telescopes. They now have significantly improved sensitivity, larger bandwidths and wider fields of view. The Murchison Widefield Array (MWA) and the pan-India Sky Watch

Array Network (SWAN) are some examples of recent large-scale radio telescope projects in which astronomers at RRI have been actively engaged.

Murchison Widefield Array (MWA)

The MWA radio telescope or the Murchison Widefield Array radio telescope, that is a precursor to the SKA-telescope, has been gathering weak radio signals from deep space since 2014 when it became scientifically operational and these are being analysed by astronomers at RRI and in the US and Australia. RRI along with Harvard and MIT in the US as well as institutions in Australia and New Zealand was involved in the successful installing and commissioning of the telescope in 2013. The MWA has presented to researchers an eye on the universe's past when the primordial cosmic gas experienced a dramatic evolution as the first stars and galaxies formed in the early universe. RRI's participation in the science goals of the project remain critical including defining techniques and methods for extracting the best out of the data generated.

Besides this, MWA data is also helping us study the structure of the intergalactic gas in our Milky Way galaxy and galaxies and clusters of galaxies beyond, and the influence of the Sun on inter-planetary weather close to Earth.

X-Ray Polarimeter (POLIX)

Several types of cosmic X-ray sources are expected to have some linear polarisation, with very strong polarisation in some sources like accretion powered X-ray Pulsars and Blazars. Important breakthroughs may be made in some key scientific aspects of these sources from their X-ray polarisation measurements. In spite of this, X-ray polarisation measurement is an as yet unexplored area. To date, only one experiment for X-ray polarization measurement has been done and the Crab Nebula is the only source with a definite measurement of its polarisation. RRI astronomers are developing methods of detecting polarized X-rays from celestial bodies and building X-ray instruments for detecting these polarized X-rays. For this, the development of an X-ray polarimeter sensitive in the range of 5-30 keV is underway, and has been approved by the Indian Space Research Organisation for launching within the next three years. The design and fabrication of the engineering space-ready model is now under progress. Developmental work for the polarimeter that has been completed in the last year include calibration of the collimator, fabrication of space qualified front end electronics, a self-calibration software for determining the position of the X-ray sources and simulations to provide a realistic estimate of the sensitivity of the polarisation measurement. Separately, another technique based on detection of the tracks of emitted photo-electrons is also being developed as a strategic initiative for future missions.

ASTROSAT

This ISRO satellite mission for multi-wavelength astronomy is designed for studies of Neutron Star X-ray binaries, AGNs (Active Galactic Nuclei), clusters of galaxies, stellar coronae, sky surveys etc. RRI has been working with two teams at ISAC, Bangalore and SAC, Ahmedabad on the Large Area X-ray Proportional Counter (LAXPC), one of the ASTROSAT payloads, which is being used for X-ray timing and low-resolution spectral studies over a broad energy band. LAXPC is designed to have a large photon collection area enabling detailed studies of high-energy features in X-ray light curves of bright and medium intensity point X-ray sources. RRI's contribution to the LAXPC has been in the timing and spectral calibration of the Astrosat-LAXPC instrument and a software design for LAXPC data reduction in collaboration with ISAC, ISRO. The main goal of the timing qualification and calibration work is to minimize systematic uncertainties in the timing response of LAXPC detectors and the processing electronics. In the last year, the group at RRI has also carried out simulations of the energy response of LAXPC detectors and used the ground calibration data to fine-tune the simulation. The simulation data has then been used to create the energy response matrix of the LAXPC detectors.

15-Metre Fan-Beam Telescope

Members of the Astronomy & Astrophysics group at RRI have proposed two new optical designs for radio telescopes that use a Fan Beam Telescope (FBT) as a component. Recent work in this area by RRI astronomers consists of a new scheme that uses two FBTs in cross configuration. This configuration can form two orthogonal fan beams on the sky, which may be cross-correlated to make a large instantaneous map. The set-up has been named "An efficient linear array imager (ELI) for Radio Astronomy". Efforts have been made through 2015-16 to build a cm-wavelength telescope at

Gauribidanur on the basis of the working principles of ELI.

Cosmic Radio Background Distortions

DISTORTION (Detection of Spectral signaTures of cOsmic baRyon evoluTION) is a collective within the Astronomy & Astrophysics group, working together towards the goal of building precise spectral radiometers to detect weak spectral distortions in the Cosmic Radio and Microwave Backgrounds arising from the Epochs of Recombination all the way to Reionization. Detection would also help astronomers to decipher the physical processes during the Dark Ages and subsequent EoR, which are necessary to understand the formation of first stars and galaxies as well as the evolution of the diffuse intervening medium to its present state. The global or all-sky 21 cm from cosmological reionization is a spectral distortion of 10's to at most about 100 mK signal and this is present in the cosmic radio background in the frequency range 30-250 MHz as a trace additive component. Towards detecting this signal researchers at RRI are working on the experiment SARAS (Shaped Antenna measurement of the background RAdio Spectrum) where they are continually designing, deploying, trialling and improving a spectral radiometer system consisting of a frequency independent antenna, self-calibratable receivers and a broadband precision digital spectrometer. The goal is to make observations not limited by sensitivity to the systematics of the receiver used and also to the man-made Radio Frequency Interference environment.

All of the bound-bound transitions in hydrogen and helium during cosmological recombination result in spectral features in the spectrum of the relic radiation from the Epoch of Recombination and these redshift with cosmological expansion to appear at cm and mm wavelengths today. These additive photons ought to appear as 'tiny' spectral structures in the CMB spectrum, as predicted from our understanding of the physics of recombination. The Array of Precision Spectrometers for the Epoch of RecombinAtion - APSERa - is a venture to detect these recombination lines from the Epoch of Cosmological Recombination. In 2015-16, progress has been made in designing a 2 GHz digital correlation spectrometer with an In-phase and Quadrature sampling scheme for the APSERa project. The new spectrometer once integrated with a simple analog chain will reach calibration preparedness. A discone monopole antenna has also been designed and tested against simulation results to be used in conjunction with the spectrometer.

Indian SWAN: (Sky Watch Array Network)

RRI has proposed the design, development and use of a wideband Sky Watch Array Network across India with the following objectives – a) To facilitate and conduct searches and studies of fast (typically of sub-second duration) and slow transient radio radiation originating from astronomical sources. b) To facilitate and conduct high angular resolution imaging of discrete galactic and extragalactic sources at low radio frequencies and c) To train, involve and provide hands-on experience to a large number of undergraduate and postgraduate students in all aspects of the SWAN, through their direct and active participation starting from the design stage to research using the array network.

The proposed competitive coordinated network with nominally 1000 sq. m array area at each location and operation spanning a decade in frequency over 50-500 MHz will be developed in three phases. In the first phase the plan is for a moderate setup to be realized followed by a demonstration of its essential features. During the year 2015-16 the focus has been on realizing a setup with 8 independent stations operating over a common narrow band, using available hardware from previous projects (a GBT receiver, MWA tiles and beam-formers). This set up is now being tested at Gauribidanur field station, following which relocation of the system to 8 different sites will be considered. Test observations will include targeted searches for radio transients in a few select directions of specific astronomical interest, and coordinated observations with the GMRT.

The SWAN project involves collaboration with almost 40+ technology and science institutes, such as the IITs, NITs, IISERs & NISERs, as well as many universities across India. To prepare the student base for this, appropriate schools/workshops (in co-ordination with existing programs) are being arranged to formally introduce under-graduate and master's students to radio astronomy such as basic concepts and advanced topics/techniques along with hands-on experience with systems. The first such school was conducted in June 2015 at RAC-Ooty. 11 students from IITs, IISERs, IIST, UNIs, and other colleges participated in the school. The next such school is scheduled for 2016 summer.

LIGHT AND MATTER PHYSICS

Members of the Light and Matter Physics (LAMP) group at RRI are pursuing research in an area of light-matter interaction which is a combination of Atomic, Molecular and Optical (AMO) physics on one hand, and intense laser produced plasmas on the other. Light-matter interactions are being investigated by this group in both classical and quantum domains using experiments as well as numerical and theoretical analysis. The interactions are studied at very high plasma temperatures, room temperature, and at extremely low temperatures attained through laser cooling methods. The use of light from the highest energy densities to the single photon regime allows an impressive range of energy scales to be investigated.

The research of the LAMP group stresses on demonstration of quantum logic using ultra-cold atoms loaded in optical lattices and various nano-traps, investigation of transport and localization properties of light in various random media, ultrafast laser induced plasmas from solid targets, nonlinear optical properties of nano materials, laser cooling and trapping of atoms, cold collisions, ion trapping, atoms in cavities, response of cooled atoms to external fields, quantum optics with neutral atoms and non-classical light sources, manufacture of single photon sources based on spontaneous parametric down-conversion and their applications to fundamental tests of quantum mechanics, quantum information and computing and quantum communication and quantum simulation of condensed matter physics using degenerate gases, and precision measurements.

RESEARCH AREAS

Electromagnetically induced transparency (EIT)

EIT is a quantum mechanical phenomenon where, under specific conditions, absorption line of a material can be cancelled, changing it from opaque to transparent at that particular frequency. EIT can be observed when two highly coherent lasers are tuned to interact with three or more quantum states of a material. A concerted effort is on at RRI to understand this phenomenon both from a theoretical and experimental point of view. The LAMP group has recently expanded its horizons within EIT to address one of the unique features of the quantum optics behind EIT – coherent, non-linear atom-optics in the low intensity regime. Due to elimination of linear order susceptibility by quantum interference, it becomes possible to induce higher-order interactions in EIT systems at very low intensities

Quantum Optics

Quantum optics is a field of study in physics that applies quantum mechanical tools to understand phenomena involving light and its interaction with matter. Major Fields of interest in quantum optics include manipulation of elemental particles like atoms, ions and molecules and the use of quantum optics to build further upon our current understanding of quantum information. For this purpose, experiments have been done involving a phase controlled, high-contrast non-linear switch in an atomic Delta system where Rubidium atoms (^{85} Rb), which can interact with both optical and microwave frequencies, form the system in question and the phenomenon of EIT is utilized to achieve the transfer of quantum correlations.

Another line of quantum optics research in LAMP focuses on the optical gain and enhancement from atom-optical-microwave interaction in a Delta system. Although line-narrowing has already been observed by the group, they are in the process of establishing true gain in this system by explicit measurements of input and output optical fields. A third application oriented study that the group has embarked upon is that of finding non-Markovian signatures in atom-light interaction in a V-level atomic configuration and their possible relevance to light absorption in photosynthesis.

A preoccupation of quantum effects in light and matter has naturally led the LAMP group to explore some foundational questions in quantum mechanics. One such area of current interest is that of quantum or weak measurements, or measurements on a quantum system made by a measuring device that causes very little perturbation to the system. Weak measurements through non-Hermitian operators are being studied both theoretically and experimentally by the group in various systems, for example via analysing the interference pattern from a Marc-Zehnder interferometer.

Laser Cooling and Trapping

Laser cooling and trapping is a technique that has gained huge popularity throughout the world of physics

in the last decade. Presently, atoms can be cooled to extremely low kinetic temperatures (150 microK) and trapped for a time period of the order of seconds. There are some techniques to cool and trap atoms of alkaline elements, the most common one being Doppler cooling in a Magneto Optical Trap (MOT). An important experiment currently being conducted at RRI using a Magneto Optical Trap is that of time-delayed intensity-interferometry of emission from laser-cooled atoms.

Hybrid Trapping Of Atoms and Ion

A hybrid trap experiment is one which combines cold atoms, ions and molecules and studies their interaction to great accuracy. Ion molecule and ion atom processes in hybrid traps are also being investigated by the LAMP group at a very fundamental level and a rich variety of phenomenon are being studied. Research at RRI has led to accurate measurements of the collision rates between atoms and ions in a cavity. Precise experimentally viable strategies to achieve a trap system that can carry forward this ion-atom system to the quantum collision limit have also been formulated. Applications of the above experiment include the recently achieved collisional cooling of light ions such as $^{39}K^{+}$ by co-trapped heavy atoms - ultracold neutral ^{85}Rb atoms. The group has also experimentally realised the direct photodissociation of trapped Rb_2^{+} molecular ions in the presence of cooling light for the *Rb* magneto-optical trap (MOT). The group is now working on the state selective collision rate measurement in ion-atom mixtures in a hybrid trap and uncovering the symmetry conditions in an interacting atom-ion system mediated by ion-atom collisions of a cold dilute gas of atoms.

Cavity Physics and Cavity QED

Hybrid trap experiments, as mentioned above, can access the quantum electrodynamic regime for atom-electromagnetic field interactions. Using cold ions, atoms and molecules simultaneously cooled and trapped with photons in a high Q optical cavity, the non-classical nature of atom-field interactions are being tapped. This is the first such experimental set-up of its kind and provides a complete system for the study of cold dilute classical and quantum gases.

An optical Fabry-Perot cavity built around a spectroscopy cell containing enriched rubidium vapour acts as the stage for one of the initial experiments. Light resonant with a specific ^{87}Rb transition is controlled by the transverse intersection of the cavity mode by another resonant light beam. Negative logic switching through destruction of transmitted light intensity and positive logic switching through a build-up of cavity mode intensity, using the transverse light as a control, has been demonstrated. Such an All-Optical-Switch (AOS) is a key component for computing architectures with photons and has the possibility for many practical applications.

Light Propagation in Random Media

Multiple scattering of light in random media, like fog, reduces visibility because propagation of light in random media is diffusive rather than ballistic. This in turn leads to some interesting phenomena like mirrorless lasing, Levy statistics and weak and strong localization. Experiments using colloidal suspensions of dielectric or magnetic microspheres, both active and passive, as well as Monte Carlo simulations and theoretical analyses are the different methods being employed to probe this process of light propagation. For the case of real-time imaging through fog, the LAMP group at RRI has successfully imaged through strongly scattering media in real-time, obtaining images at rates faster than the critical flicker frequency of the human eye, so that the images are perceived as continuous. This is an important breakthrough in the design of continuous, flicker-free display devices that can aid navigation under poor visibility.

Fundamental Tests of Quantum Mechanics Using Quantum Optics Based Tools

Quantum mechanics is a cornerstone of modern physics. Just as the 19th century was called the Machine Age and the 20th century the Information Age, the 21st century promises to go down in history as the Quantum Age. However, can we really claim to fully understand quantum mechanical principles? How much do we really believe of what we know? Answers to such questions require us to revisit the fundamental postulates of quantum mechanics and perform precision theoretical and experimental investigations to come up with the right bounds. In the LAMP group, a part of the focus is to attempt such investigations using single light particles i.e. single photons as tools. Such tests are important in the current theoretical physics scenario where there is substantial interest in unification of quantum mechanics and general relativity.

A major result in this field from the LAMP and TP

groups combined has been a more complete understanding of the limitations of a naïve application of the superposition principle in slit based interference experiments. Boundary conditions for the wave function in the three different scenarios of having both slits open and the two individual slits open one at a time are different and as such superposition principle should not be directly applicable in this case. Building upon their work on this concept from 2014-15 researchers from the LAMP group along with collaborators from the Indian Institute of Science have now come up with an analytic formula for the Sorkin parameter, kappa that quantifies the contribution from the non-linear, non-classical paths to the above quantum interference experiment. The analytic formula makes the predicted experimental demonstration easier as the parameter dependencies on different experimental quantities can now be estimated. The researchers have also shown beautiful overlap between results obtained from their analytic formula and those obtained using much more resource intensive Finite Difference Time Domain simulations. Experimental verification of this work is currently under execution in the LAMP lab using both infra-red and microwave optics based tools.

Quantum Information and Quantum Computation

The main thrust here is research on experimental and theoretical aspects of quantum information and quantum computation. The systems of choice are quirts (three dimensional quantum systems), based on spatial degrees of freedom of the single photon. The LAMP Group has been one of the first labs in the country to develop the technology of entangled and single photon sources, both Type I and Type II, based on spontaneous parametric down conversion in bulk non-linear crystals. The single photons and their various degrees of freedom are used to investigate aspects quantum communication, quantum information and quantum computation. In the near future, the LAMP Group wishes to enter the domain of quantum communication and develop both terrestrial and satellite based technologies.

Nonlinear Optics

Nonlinear optical (NLO) transmission of materials finds applications in optical switches, optical limiters and saturable absorbers. Optical nonlinearities of novel nanoparticles and nanocomposites are being investigated in the LAMP group. Typically, materials show tunable, enhanced characteristics in the nano phase, which can be very different from their properties in the bulk form. Ultrafast (100 fs) and short (5 ns) laser pulses are employed to identify features of nonlinearity in different time domains, employing the techniques of Z-scan, four wave mixing and pump-probe spectroscopy. These investigations have also thrown new light into the role of lattice defects in determining the nonlinear absorption behaviour of novel materials like nine-atom silver quantum clusters (QCs), graphitic carbon nitride (GCN), reduced graphene oxide (rGO) nanosheets, Ag2S-CuS nanocomposites, CdO nanomorphotypes, and similar systems. In a work of far-reaching importance for graphene based electronics, the LAMP group has experimentally proved an impairment of electron mobility in doped-graphene due to increased electron-defect scattering.

Laser Induced Plasmas

Plasma, the fourth state of matter, is routinely produced in the LAMP labs by irradiating suitable targets with powerful pulsed lasers. These plasmas which exist only for a few microseconds can be considered as short-lived stars, and their study is often called 'Laboratory Astrophysics'. Ultrafast laser produced plasmas ejected from metal targets (Nickel, Zinc and Aluminium) irradiated in vacuum are found to contain electrons, ions, visible radiation, and high energy photons in the soft and hard X-ray regimes. Spectroscopic investigation of the plasma can be used to identify constituent elements of an unknown target while time-of-flight studies of the temporal evolution of the plasma in the nanosecond regime gives information on the velocity, acceleration and recombination rates of the constituent ions, electrons and neutrals (recombined ions).

Quantum Simulation of Condensed Matter Problems Using Degenerate Gases

A new experiment facility is being set up by the LAMP group towards creating a Sodium-Potassium gas mixture at nano-Kelvin temperature. At this very low temperature well below critical temperature for Bosonic species and Fermi temperature of Fermionic species, the behaviour of the trapped cloud can be completely described by quantum theory and thermal fluctuations can be ignored. The system would then be a model system for investigating purely quantum mechanical phenomena that are analogues for complex condensed

matter physics questions such as unconventional superconductivity, disordered-interacting phase diagrams etc.

SOFT CONDENSED MATTER

In recent years, soft condensed matter physics or "soft" physics has emerged as a field of research in its own right within the broader field of condensed matter physics. Soft materials, constituted by macromolecules that are held together by weak inter-macromolecular forces, are characterized by complex structures and phase behaviours. Colloidal suspensions and emulsions such as milk and paint, polymeric and biological materials, foam and liquid crystals are some common examples. The sizes of the macromolecules that constitute these materials are typically between a few nanometers and a few micrometers. In contrast to atomic systems whose relaxation times are of the order of picoseconds, soft materials relax on time scales that usually lie between 10^{-8} and 10^{3} seconds, which gives rise to long-lived metastable states. The structure and dynamics of these materials can therefore be easily studied using relatively simple laboratory techniques. Usually characterized by elastic constants that are many decades lower than those of traditional atomic solids, soft materials are also viscoelastic and easily deformable and can be used in the study of a variety of non-equilibrium phenomena. Thermal fluctuations too play an important role in determining their properties.

The ease with which inter-constituent interactions can be modified in soft materials ensures that newer materials with interesting and useful properties can also be engineered from them. Their structural complexity, symmetries and mechanical flexibility also make soft materials ideal model systems for applications as well as tests of ideas from statistical physics and condensed matter theory.

The soft condensed matter group at RRI is engaged in research on colloids, polymers, nano-composites, amphiphilic systems, synthesis, characterization and physical studies of liquid crystals and other exciting new areas such as biological physics.

RESEARCH AREAS

Liquid Crystals, Nano-Composites and Polyelectrolytes

Experimental and theoretical studies have been undertaken at RRI to deal with the structure- property relations of 'soft' materials, which are easily deformable by external stresses, thermal fluctuations, electric, and magnetic fields. Among these soft materials are thermotropic liquid crystals consisting of highly anistropic organic molecules, banana mesogens with spontaneous breaking of macroscopic chirality, nano-composite materials, liquid crystals formed of bent-core hockey stick shaped molecules, polymers and biomaterials such as biomolecules and cells. The interplay between the different degrees of freedom and various constraints present in these systems often give rise to rich and complex behaviour that can be exploited for potential technological applications. Examples of such work are the recent studies of pseudo-polar tilted smectic phases exhibited by bent core hockey stick shaped molecules and the synthesis and characterisation of novel isoxazole-based banana liquid crystals isolated from naturally occurring curcumin – a plant with medicinal properties. The latter could have considerable biological importance.

The chemistry wing of the Soft Condensed Matter Group is involved in the design, synthesis and characterisation of novel liquid crystalline materials that exhibit remarkable electronic and optoelectronic properties. This group has synthesized a number of monomeric, oligomeric, polymeric and ionic liquid crystalline materials. During the period 2015-16, certain iodine-free discotic electrolytes were synthesized, characterized and applied in dye-sensitized solar cells. Self-assembling, disc shaped liquid crystal (LC) materials meant to design bulk hetero-junction or BHJ solar cells and LCs derived from new U-shaped azobenzene showing significant photoswitching properties are other examples of materials created by the group targeting future solar cell applications.

The incorporation of nanomaterials such as metal-nanoparticles like gold, silver or copper, quantum dots of materials such as thiolated graphene oxide, luminescent CdTe or CdSe and carbon nanotubes, in the supramolecular order of liquid crystals is likely to lead to novel materials for many applications. With this view, a research program has been initiated to prepare and

functionalise these nanomaterials with discotic as well as nematic molecules and disperse them in monomeric, oligomeric and polymeric discotic liquid crystals with properties such as ferroelectricity. The dispersion of such functionalised nanomaterials has been found to enhance physical properties such as their thermodynamic properties, elastic constants, dielectric properties, conductivity and photoconductivity significantly leading to applications in fields such as photovoltaics.

One of the present research interests of the SCM group is in investigating the synchronization of conformational chirality in liquid crystals made up of achiral molecules. Using two known bent-core liquid crystals or BCLCs – NNMTB and PDMBC in various concentrations – the group has shown the existence of three types of lamellar mesophases: a dark enantiomeric (DE) phase, a dark conglomerate (DC) phase, and third - a birefringent lamellar SmCP with flat layers. The progressive evolution of homochirality as a function of the relative concentration of the achiral constituents as observed in this system clearly shows the role of an intrinsic coupling of molecular conformations in the system with its chirality. This property can thus provide a control for tuning macroscopic chirality and for optimizing chiroptical properties for applications.

Another area of interest is in understanding the unusual occurrence of a reentrant lamellar phase in bent-core liquid crystals. Phase reentrance is a state where a less ordered phase characteristic of a higher temperature reappears again below a more ordered one at a lower temperature. This is extremely rare in the case of BCLCs and very few examples are known to exist. The group has synthesized a novel achiral BCLC compound that apparently shows reentrance characteristics as evidenced by their initial electro-optic and dielectric studies.

Phase Behaviour of Ionic Surfactants

The effect of adsorbing counterions and polyelectrolytes on the phase behavior of ionic surfactants is being investigated using a variety of experimental techniques. The main objective of these studies is to find conditions under which novel aggregate morphologies and phases can be stabilized in these systems. Instead of looking at a single charged surface as in earlier experiments, recently this group is using a novel setup to probe the adsorption process – that of a periodic stack of charged surfactant bilayers automatically throwing open the possibility of employing X-ray scattering techniques.

Structure of DNA-Surfactant Complexes

Structure of DNA-cationic surfactant complexes is being investigated using X-ray diffraction. The main focus of the study is to stabilize different structures of these complexes by changing parameters such as the size of the surfactant molecule and the nature of its counterion.

Organization of Sterols in Membranes

The phase behaviour of lipid membranes containing different sterol molecules is being studied, with a view to understanding the organization of these biologically important molecules in the membrane. Further experiments are underway to probe the orientation of these molecules in the membrane.

Organization of Mononucleotides on Lipid Membranes

The group has studied the organization of mononucleotides on lipid membranes showing that these molecules form dense patches on the membrane surface, which is an interesting result since such an arrangement is a prerequisite for their polymerization into long chains. The experiment could have relevance in understanding the physics behind the formation of self-replicating long-chain RNA-like polymers in the cellular environment.

Colloids and Complex Fluids

Experimental investigations of the structure, dynamics and rheology of non-Newtonian fluids and aging suspensions, soft glassy rheology, flow-structure correlations in complex fluids, interfacial instabilities, the design of viscometers to measure complex flows, the stability of colloidal suspensions, the sedimentation of colloidal gels, micellar packings, controlled, targeted drug delivery using copolymer micelles as vehicles for drug delivery, the physics of granular media are being carried out.

Experimental tools such as static and dynamic light scattering, rheology, cryogenic scanning electron microscopy, ultrasound attenuation spectroscopy and high-speed imaging are being used extensively for these studies. Many of these investigations involve collaborations with engineers and theoretical physicists and materials science.

Some specific experiments that were performed in the last year include falling ball experiments on aging Laponite (synthetic clay) colloidal suspensions, kinetics of the glass transition of fragile soft colloidal suspensions of Laponite and dynamical heterogeneities in such suspensions when pushed to a glassy state. Apart from Laponite, natural clay and colloidal gels formed of aqueous solutions of Na-montmorillonite nanoclay particles are also being explored with special emphasis on studies of the exfoliation and stability of natural clay in aqueous suspensions, effect of electrolytes on the microstructure and yielding of colloidal clay and aggregation and stability of colloidal clay-water suspensions in the presence of salt. The latter two studies could throw light on certain geophysical phenomena such as quicksand, river delta formation and even on physical factors behind landslides etc.

Biophysics

A physicist's approach to biological systems provides a novel perspective on how living machinery inside a cellular factory works. The group at RRI aims at achieving a quantitative physical description of dynamical phenomena occurring in cells at various levels. They are interested in nanoscale molecular structures that dominate interactions in DNA, protein segregation and self-assembly, DNA-protein complexes such as chromatin fibres, and signaling at the level of the cell membrane, aided by active cellular dynamics. They also investigate dynamical phenomena in neuronal cells leading to shape transitions and active mechanical responses. To quantify these studies, novel state-of-the-art techniques are developed in-house: for example, single molecule resolution nano-devices that help in deciphering secrets of biological nano-world and ultra-sensitive force measurement methods to probe mechanical responses of single cells. A shear device developed and constructed in-house that can reveal cell adhesion properties when used in conjunction with fluorescence microscopy techniques is the latest addition to this list. The device can create well-defined cell geometries when used with micro-patterning techniques but more importantly, can help quantify cell adhesion through measurements on cell detachment under shear conditions.

A recent study on axonal shape instabilities by the Biophysics group at RRI has yielded an important result. Using genetic means to express fluorescent synaptic vesicles the study has shown that transport in axons is not affected by 'beading' suggesting that 'traffic jam' is not the cause behind 'beading' as previously hypothesized by other researchers in the field. The earlier hypothesis simply translated, refers to beading as the disruption of transport within the axon cytoskeleton leading to accumulation of cargo or 'bead' formation. This is the first characteristic of axonal injury and the first step towards axonal degeneration. However, recent experiments at RRI show that these shape instabilities in axons may be a result of breakages in the microtubules in the axon cytoskeleton itself.

Glass and quartz nanopores of sizes about 6-800 nm constructed by the group have been characterized to enable detection of individual DNA molecules translocating through these nanopores. Efforts are also being made to measure the elastic properties of biological cells by forcing them to traverse through micropores against a bias voltage, using resistive pulse techniques.

Theoretical Studies

Theoretical work in the SCM group primarily focuses on the theory of elasticity and topological defects in soft matter. Orientational (such as nematic, vector, hexatic) tangent-plane order on two-dimensional membranes deformable in three dimensions suffers frustration on curved membranes. Recently, the group has put forth a theoretical model to explain the topological instability in lyotropic smectic-A liquid crystals under hydration conditions, especially the growth of tubule-like structures and beads.

THEORETICAL PHYSICS

The major areas of research pursued by the Theoretical Physics (TP) group are statistical physics, including non-equilibrium statistical physics, soft condensed matter and quantum many-body physics, quantum gravity, general relativity and foundations of quantum mechanics. The TP group, by the very nature of its work, often interfaces and collaborates with experimental groups within RRI such as the Light and Matter Physics group, especially in the areas of foundational questions in quantum physics, and the Soft Condensed Matter group, in areas such as biophysics and non-equilibrium statistical physics. There are also collaborations with experimentalists working in these areas outside the institute.

RESEARCH AREAS

Statistical Physics

The TP group is currently engaged in research on the equilibrium and dynamical properties of polymers. A problem that the group is working on is that of ring-closure probability of semi-flexible polymers using the Worm-like Chain model or the WLC model. The WLC model consists of a completely flexible isotropic rod as the connector between two carbon atoms in the polymer chain. The semi-analytical results obtained so far show a power law (a relation between two variables such that a change in one results in a proportionate change in the other independent of initial values of either variable) decay in the ring-closure probability with the contour length of the polymer in question (i.e. the maximal physically possible extension of the polymer) over a range of length scales. The above study can have implications for biophysical studies of DNA and actin filaments.

Non-Equilibrium Statistical Physics

A theoretical understanding of some basic questions in standard non-equilibrium statistical physics is one of the aims of the TP group. To this end research has been carried out by the TP group on large deviations for Markov processes (random statistical processes whose current state is unaffected by memory or rather 'memory-less' systems) with resetting (restarting or initialization), random walk with random resetting to the maximum position, exact probability distribution for two-tag displacement in a constrained single-file motion of point particles where the point particles have hard-core repulsive inter particle interaction preventing particle crossings, and finally the fluctuation theorem for entropy production of a partial system in the weak coupling limit. The last work shows that when one small system in contact with a heat bath is weakly coupled to a similar one, it becomes possible to infer the presence of such weak coupling by observing the violation of the steady state fluctuation theorem for the partial entropy production of the observed system in whole.

Theoretical Condensed Matter and AMO Physics

The TP group has recently explored strongly interacting photons in one-dimensional geometries that are optically bound in one direction supporting this theoretical gedanken experiment with corresponding experimental realizations such as interacting Rydberg atoms in a cold gas. Another recent project of note is the study of the logarithmic growth of entanglement in a disordered chain of free fermions with long-range hopping. The work is a numerical investigation of the dynamics of entanglement in a chain of spin-less fermions with predetermined long-range hopping and interaction energies but with random on-site energies.

Quantum Gravity

The TP group at RRI carries out research on quantum gravity from two distinct viewpoints, Loop Quantum Gravity (LQG) and Causal Set Theory (CST).

LQG is a method where standard Hamiltonian ways of quantization are applied to the classical gravitational field without resorting to perturbation theory. The consequent absence of a spatial geometry in LQG has been addressed through some new ideas and tools by the TP group, while the absence of a background time and an overall recovery of the space-time continuum in the classical limit are the two issues being looked into currently. Entanglement entropy, coherent states and their effect on gravity and quantum dynamics and long-distance correlations in a polymer-parameterized field theory constitute the efforts by the TP group in this area during the last year. The work evidently employs statistical physics concepts such as entropy and polymer theory.

In the CST approach to quantum gravity, on the other hand, one replaces continuum space-time by a discrete substructure, which is a locally finite, partially ordered set, the Causal Set. The here continuum arises as an approximation, rather than as a limit since the cut-off is a physical input rather than a mathematical convenience as in other discrete approaches. Most recently there has been work at RRI on the construction of a discrete propagator in curved space-time by using a local Green's function in 2 and 4 space-time dimensions and assigning appropriate probabilities to 'hopping' and 'stopping'. During the past year, research has also been done at RRI on the large N limit in 2D causal set quantum gravity. The group at RRI had earlier found that 2D causal set quantum gravity shows a phase transition from a continuum phase to a crystalline non-continuum phase that affects the Hartle Hawking ground state (Hartle Hawking ground state is the ground state for the Hartle Hawking wave function for CST) with

implications for the role of quantum gravity in explaining the observable universe.

Another line of investigation motivated by causal sets and quantum cosmology considerations is the quantum measure approach to quantum foundations. Here, one places quantum theory in parallel with stochastic physics with its attendant interpretational generalizations. Work is on at RRI to understand how this framework can be used to obtain covariant observables in quantum gravity. The statistical physics concept being used in the work consists of percolation (trickling of particles or particle-properties through an intervening medium which, in the process, broadly performs a 'filtration').

Foundational Questions in Quantum Mechanics, Quantum Measurements, and Quantum Equivalents of Classical Systems

The dynamics of a quantum particle in a box with moving walls and the existence of an associated non-trivial Berry phase with the dynamics (Berry phase or geometric phase is the instantaneous phase or state of motion that the particle picks up upon undergoing a cyclic motion without any heat exchange resulting only from the geometrical properties of the system being studied) is one of the foundational questions in Quantum Mechanics that the TP group in RRI has been working on. The result shows that specific boundary conditions need to be maintained in order to preserve unitarity, or in other words, to ensure that the sum of all probabilities associated with the motion of the particle adds up to unity.

During the period 2015-16, the TP group at RRI has also arrived at an extremely important result with far-reaching consequences in how we understand the process of measurement in quantum systems. In an analytical study treating the spin of a silver atom as a quantum system in the context of the Stern-Gerlach experiment, the TP group at RRI has proposed the concept of a coarse quantum measurement. It appears that quantum measurements are limited in their resolution by bounded resources, which results in a non-unitary evolution of the system in question, not governable by the Schrodinger equation. It is proposed that the coarseness of the detection process is what renders a quantum system non-unitary.

This year, the TP group has also begun working on diffusion at low temperatures where a quantum version of the law of diffusion based on the fluctuation dissipation theorem is being constructed.

General Relativity

Simple Euclidean methods can successfully reproduce entropy and temperature of black holes derived by completely different methods. Motivated by this, the TP group has used a rotated time direction on a standard Wick rotation (Wick rotation is a method of solving a mathematical problem in Minkowski space or in the fabric of space and time by employing a simple transformation of an imaginary number variable to a real number variable in the solution of the Euclidean counterpart of the problem) to arrive at a real Euclidean metric for describing a rotating black hole.

ASTROPHYSICS AND ASTRONOMY

Overview

There are broadly three aspects to the research of the Astronomy & Astrophysics group –

Theoretical Astrophysics that involves development of analytical models and computational numerical simulations describing the dynamics, physical properties and underlying phenomena in celestial objects like stars, planets, galaxies, interstellar medium etc. Theorists also work on answering fundamental questions on the formation and evolution of the Universe, a branch of astrophysics called cosmology.

Observational astronomers on the other hand use telescopes built across the globe to study radiation from space across the entire electromagnetic spectrum – low frequency (long wavelength) radio waves to very high frequency (short wavelength and highly energetic) gamma rays. These observations test existing theoretical models and also give rise to new questions that call for answers.

The third aspect involves the design, construction and operation of telescopes, which are often built for very specific purposes, and are strategically located around the world and in space. RRI has an Astronomy & Astrophysics group that embraces research work in all these three facets.

Research Areas

Theoretical Astrophysics

Cosmology

Cosmology is the study of our Universe as a whole – including the dynamical and astrophysical evolution from the Early Universe to its present form. A recent result in this field is that most of the neutral hydrogen in the redshift range 1.18-1.34 is not contained in star-forming galaxies but instead remains concentrated in smaller galaxies. This has implications in understanding the composition and source of neutral hydrogen in star-forming galaxies at redshifts close to 1.3. Other questions being addressed in this field include a study of the impact of alternate models of dark matter on HI distribution at high redshifts and the applicability of 2p-2s masers as a probe for primordial black holes. This year, data from the Murchison Widefield Array have been analysed for detection of redshifted 21-cm from the Epoch of Reionization (EoR). A new pipeline to analyse 3 hours of raw data collected using both tracking and drift scan strategy has been formulated this year.

The origin of magnetic fields in the universe remains a mystery. It is possible that they are of primordial origin and therefore affects cosmological observables, such as CMBR (Cosmic Microwave Background Radiation) anisotropies and large-scale structure formation. Cosmology has turned into a precision science in the past twenty years and observations can now potentially reveal the nature of these fields. The effects of magnetic fields on different physical processes, structures and signals are being studied. Some of these are cosmological gravitational lensing, Lyman-alpha clouds, neutral hydrogen signals from the epoch of reionization and the early formation of molecular hydrogen.

Cosmic rays, gamma rays and neutrinos

Highly energetic particles (protons, nuclei, photons and neutrinos) detected on Earth are accelerated in galactic and extragalactic environments. Theoretical modelling of the origin, production and propagation of these high-energy particles is used to interpret observations from gamma ray detectors, such as Fermi LAT, HESS, MAGIC, AGILE and the IceCube neutrino telescope. The applications of these models include galactic sources, extragalactic sources like gamma ray bursts, and the emission mechanisms and environment in quasars associated with active galactic nuclei. During the period 2015-16, research has been conducted on multi-wavelength emission associated with highly energetic particles such as protons, nuclei, photons and neutrinos in blazars and quasars, with an aim to understand the underlying acceleration mechanisms of such particles in jets. In particular, studies on the proton synchrotron radiation from extended jets of PKS 0637-752 and 3C 273 have been performed using standard methods as well as novel approaches that take into account stochastic and shear acceleration of protons in these large scale quasar jets. Other intriguing questions being investigated include the properties of high-energy neutrinos from the now-famous gravitational wave event GW150914 that could possibly be associated with a short gamma-ray burst detected by the Fermi Gamma-ray Burst Monitor (GBM) 0.4s after the GW event and within localization uncertainty of the GW event.

Galaxies and their surroundings

The interaction between galaxies and their surroundings plays an important role in the evolution of galaxies and the intergalactic medium. The interactions involve the flow of gas acted upon by radiation pressure, cosmic rays and the galaxy's gravitational field. These complex processes are studied using both analytical methods and hydrodynamic simulations. Of interest are violent gaseous outflows from galaxies. Research by the Astronomy and Astrophysics group addresses their origin, evolution, feedback effects on the parent galaxy, and transport of heavy elements such as carbon, oxygen to the outer parts of the galaxy and beyond. Recent research in this area is addressing problems such as the Fermi bubble or the intensely bright gamma-ray feature rising from the centre of the Milky Way that also happens to be rich in X-rays and microwave emission; suppression of galactic outflows by the hot circumgalactic gas in galaxies; merger of supernovae in massive star clusters to form superbubbles; diffuse X-ray emission from galaxies with its root, once again, in the hot circumgalactic gas and exploration of possible

signatures of the circumgalactic medium in the CMB through cross-correlation analyses.

Stellar dynamics in galactic nuclei

The nuclei of galaxies have dense clusters of stars orbiting supermassive black holes (BH); two nearby examples are the Galactic centre and the nucleus of the Andromeda galaxy. Gravitational force between the bodies mainly governs the structure, dynamics and evolution of the stellar system. Both dynamical and statistical mechanical methods are being used to formulate a theory of the long-term evolution of these Keplerian stellar systems with long-range interactions. Phenomena studied include collisionless dynamics of the star-cluster, instabilities, relaxation to equilibrium and fuelling of the BH, which contributes to its mass and spin.

Exoplanetary Dynamics

Most exoplanetary systems in binary stars consist of one or more planets orbiting a primary star with a wide binary stellar companion. The planetary eccentricities and mutual inclinations can be large, and may be due to gravitational forcing by the binary companion star. However, the role of a wide binary star on planetary evolution had until now remained largely unexplored. During 2015-16, work has been done in RRI on presenting a mechanism that has the potential to explain several observed features of exoplanetary statistics especially in binary stars with a single planet system. The work also seeks to explain the whys and hows of the discernibly lower number of binary stars with multi-planet systems.

Observational Astronomy

Diffuse Radio Emission from Galaxy Clusters:

Galaxy clusters are some of the largest gravitationally bound structures in the Universe. As many as hundreds of galaxies can be bound in a volume with linear extents of a few million light years. The space between the galaxies, the Intra Cluster Medium (ICM), is often home to sources of bright diffuse radio emission. This radio emission is known to be of non-thermal origin and is due to relativistic electrons radiating in the cluster magnetic field. Observations and interpretations of the origin of diffuse radio emission from galaxy clusters has implications on understanding of large scale magnetic fields in clusters, cluster mergers, and cluster evolution. These observations are being carried out using a variety of radio telescopes like the Giant Meterwave Radio Telescope (GMRT), the Very Large Array and the Murchison Widefield Array, which was built by RRI and international partners in a collaborative project. Archival X-ray observations are used along with these radio observations to understand these intriguing sources of radio emission. An interesting example of a galaxy cluster, which is known to host a double radio relic and has been reported to contain a faint radio halo and bridge, is Abell 3667. The origin of radio haloes, relics and bridges is still under contention although galaxy cluster merger is acknowledged to be an important factor. During the period 2015-2016, Murchison Widefield Array observations of Abell 3667 have been analysed by the A&A group at RRI. Talking about the ICM also leads us to a recently conducted study on pre-merger tidal interactions between pairs of galaxies. Large amounts of gas and stars are often disturbed or displaced as tidal debris leading to changes in the morphologies and kinematics of the galaxy components such as stars and ISM. A detailed study on the Arp 65 interaction debris was concluded this past year. This year six massive star clusters have also been brought come under the magnifying glass with the aim of demystifying their diffuse radio and X-ray emission using data from GMRT and Chandra X-ray data.

Pulsars:

Pulsars are rapidly spinning high-magnetic-field neutron stars that originate in supernovae. These were originally discovered in their pulsed radio emission; however, today they have been detected in pulsed emission across the electromagnetic spectrum. Pulsar emissions provide information about their structure, the high-energy processes in the magnetosphere, their interactions with their environment and can also be used as a test platform for General Relativity. Millisecond pulsars are one of the most accurate clocks in the Universe. RRI conducts active research on pulsars and develops radio receivers and X-ray detectors that can help us understand their nature. Comprehensive studies on timing and spectral characterisation, pulse profile evolution and the pulsar spectrum of emitted X-rays are being conducted on pulsars of various types. Other studies like periodicity determination from a sequence of occasional single pulses**,** detection methods of off-pulse radio emission from pulsars vis-à-vis their reliability;

along with searches for fast radio bursts (FRBs) too are underway.

Radio Galaxy Morphologies

Amongst the population of many different types of radio galaxies it is the X-shaped radio galaxy in particular, with its two typical lobes accompanied by two others, which together give the source a shape like the letter X that is currently being investigated by some members of the Astronomy group at RRI. How the two additional lobes are generated is debatable and is of importance to understand the coalescence of supermassive black holes and generation of gravitational wave background. In the X-shaped radio galaxy, two lobes appear to be active while the other two are relics or spillovers of plasma from the main axis. Research is on at RRI to test various existing theories on the shape and structure of X-shaped radio galaxies. During the period 2015-16 total intensity and polarization data from 56 radio sources out of a whole sample of 99 radio sources have been observed using the JVLA telescope. The work is expected to throw light on the origin of the enigmatic X-shaped radio galaxies by assessing the role of various plausible causative processes, which sources have undergone radio axis change and into the causes of radio axis changes themselves, and is important for making a more detailed study of host-galaxy halos than was possible before. Searches for cores and jets that can possibly help decipher the origin of large scale X-shaped radio structures also continue.

With the availability of low frequency images of the southern sky mapped with the Murchison Wide-field Array (MWA) a comparative study of structures of radio sources at low frequencies against their counterparts in images obtained at high frequencies is being performed in order to know more about the true extent of radio sources, and/or the presence of relic radio emission in these sources.

X-ray binaries

Compact stars (neutron stars and black holes) create some of the most extreme conditions in the universe. Their high-energy emission, mostly X-rays, can be accessed using space X-ray observatories. Astronomers at RRI use observations made using a range of international space observatories to investigate topics such as orbital evolution of binary X-ray stars and orbital glitches, quasi-periodic oscillations in X-ray pulsars, self absorption in X-ray pulsars and dips in the pulse profiles, cyclotron absorption lines in X-ray pulsars, neutron star magnetic field, optical reprocessing and temperature measurements of thermonuclear X-ray bursts, variations in intensity and pulsation characteristics during eclipse/partial eclipses. The Indian multi-wavelength astronomy satellite ASTROSAT and an Indian X-ray polarimeter POLIX that is being built at the Raman Research Institute will enhance X-ray binary research at RRI substantially.

Radio Telescopes and Astronomy

Members of the Astronomy & Astrophysics group along with the Radio Astronomy Laboratory of the Institute are involved in projects concerning various telescopes throughout the world. Questions like radio signatures from the Epoch of Reionization and transient radio phenomena, particularly fast radio transients, have changed the next generation radio telescopes so that they now have significantly improved sensitivity, larger bandwidths and wide fields of view. Modern radio telescopes are now realized as phased arrays, or Aperture Arrays, where the number of beams depends only on the available processing power and signal transport, unlike earlier radio telescopes that were based on large reflectors with a single or small number of feeds. The Murchison Widefield Array (MWA) and the pan-India Sky Watch Array Network (SWAN) are some examples of recent radio telescope projects in which astronomers at RRI have been actively engaged.

Murchison Widefield Array (MWA):

The MWA radio telescope or the Murchison Widefield Array radio telescope located in Murchison Shire in the Australian outback is an array of antennas arranged as square 'tiles' consisting of a total of 2048 dual-polarization wide-band 'bow-tie shaped' antennas that operate in the frequency range 80-330 MHz. They are arranged as 128 square 'tiles' each were having 16 pairs of antennas. The antenna distribution is designed for precision imaging of a wide field of several hundred square degrees of the sky at any instant and over a wide frequency band. The antennas are connected to digital receivers which process the data before transmitting it via high-speed fibre optic cables to a centralized imaging system located 800 kilometres away at Perth. The digital receivers that take the signals from the antennas and perform complex high-speed signal processing of the data prior to transmission to the central processing unit,

which computes the imaging information, were designed and built at RRI. RRI along with Harvard and MIT in the US as well as institutions in Australia and New Zealand was involved in the successful installing and commissioning of the telescope. The construction and commissioning of the MWA was completed in mid 2013.

The MWA has been gathering weak radio signals from deep space since 2014 when it became scientifically operational and these are being analysed by astronomers at RRI and in the US and Australia. The MWA has presented to researchers an eye on the universe's past when the primordial cosmic gas experienced a dramatic evolution as the first stars and galaxies formed in the early universe. RRI's participation in the science goals of the project remain critical including defining techniques and methods for extracting the best out of the data generated.

Besides this, MWA data is also helping us study the structure of the intergalactic gas in our Milky Way galaxy and galaxies and clusters of galaxies beyond, and the influence of the Sun on inter-planetary weather close to Earth. Like previous years, numerous collaborative publications also appeared during the year gone by.

Gauribidanur Radio Telescope (GRT):

This decametre wave radio telescope at Gauribidanur was built in collaboration with the Indian Institute of Astrophysics. Operating at 34.5 MHz, this meridian-transit instrument has some tracking capabilities. When built it consisted of 1000 dipoles arranged in the form of a letter 'T'. The bandwidth is about 10 MHz centred at 32 MHz, while maximum effective collecting area is about 18,000 square metres. The E-W beam can be tilted in Hour Angle within 10° around the meridian enabling tracking for a minimum of 42 min. Members of the astronomy group currently study emissions from pulsars and search for fast radio transients using the GRT.

X-ray polarimeter (POLIX):

Several types of cosmic X-ray sources are expected to have some linear polarisation, with very strong polarisation in some sources like accretion powered X-ray Pulsars and Blazars. Important breakthroughs may be made in some key scientific aspects of these sources from their X-ray polarisation measurements. In spite of this, X-raypolarisation measurement is an as yet unexplored area.To date, only one experiment for X-ray polarization measurement has been done and the Crab Nebula is the only source with a definite measurement of its polarisation. RRI astronomers are developing methods of detecting polarized X-rays from celestial bodies and building X-ray instruments for detecting these polarized X-rays. For this, the development of an X-ray polarimeter sensitive in the range of 5-30 keV is underway, and has been approved by the Indian Space Research Organisation for launching within the next three years. Anisotropy in the Thomson scattering of polarised X-rays is one technique that could be used to measure the degree and angle of linear polarisation of cosmic X-rays. A laboratory model adopting this method has been built and tested successfully. The design and fabrication of the engineering model is now under progress. Developmental work for the polarimeter that has been completed in the last year include calibration of the collimator, fabrication of space qualified front end electronics, a self-calibration software for determining the position of the X-ray sources and determination of a realistic estimate of the sensitivity of the polarisation measurement. Separately, another technique based on detection of the tracks of emitted photo-electrons is also being developed as a strategic initiative for future missions.

ASTROSAT:

This ISRO satellite mission for multi-wavelength astronomy is designed for studies of Neutron Star X-ray binaries, AGNs (Active Galactic Nuclei), clusters of galaxies, stellar coronae, sky surveys etc. RRI has been working with two teams at ISAC, Bangalore and SAC, Ahmedabad on the Large Area X-ray Proportional Counter (LAXPC), one of the ASTROSAT payloads, which is being used for X-ray timing and low-resolution spectral studies over a broad energy band. LAXPC is designed to have a large photon collection area enabling detailed studies of high-energy features in X-ray light curves of bright and medium intensity point X-ray sources. RRI's contribution to the LAXPC has been in the timing and spectral calibration of the Astrosat-LAXPC instrument and a software design for LAXPC data reduction in collaboration with ISAC, ISRO. The main goal of the timing qualification and calibration work is to minimize systematic uncertainties in the timing response of LAXPC detectors and the processing electronics. In the last year, the group at RRI has also carried out simulations of the energy response of LAXPC detectors and used the ground calibration data to fine-

tune the simulation. The simulation data has then been used to create the energy response matrix of the LAXPC detectors.

15-Metre Fan-Beam Telescope:

Members of the Astronomy & Astrophysics group at RRI have proposed two new optical designs for radio telescopes that use a Fan Beam Telescope (FBT) as a component. Currently, RRI is engaged in building a Fan Beam Telescope - Low Frequency (FBT-LF) with the purpose of demonstrating it's functioning and the expected benefits of the new designs. Once commissioned, it will pave the way for the realization of the above two optical designs. Recent work in this has presented a scheme that uses two FBTs in cross configuration. This can form two orthogonal fan beams on the sky, which may be cross-correlated to make a large instantaneous map. This set-up has been named "An efficient linear array imager (ELI) for Radio Astronomy". Another device designed to make correlation measurements is a "One-element interferometer" where Ryle's phase switching technique is adapted to a single dish with either coherent or incoherent receivers. Efforts have been made through 2015-16 to build a cm-wavelength telescope at Gauribidanur on the basis of the working principles of ELI.

Cosmic Radio Background Distortions:

DISTORTION (Detection of Spectral signaTures of cOsmic baRyon evoluTION) is a collective within the Astronomy & Astrophysics group, working together towards the goal of building precise spectral radiometers to detect weak spectral distortions in the Cosmic Radio and Microwave Backgrounds arising from the Epochs of Recombination all the way to Reionization. Detection of signals from neutral hydrogen atoms at the time the first luminous objects in the universe were born is challenging. Detection would also help astronomers to decipher the physical processes during the Dark Ages and subsequent EoR, which are necessary to understand the formation of first stars and galaxies as well as the evolution of the diffuse intervening medium to its present state. The global or all-sky 21 cm from cosmological reionization is a spectral distortion of 10's to at most about 100 mK signal and this is present in the cosmic radio background in the frequency range 30-250 MHz as a trace additive component. Towards detecting this signal researchers at RRI are working on the experiment SARAS (Shaped Antenna measurement of the background RAdio Spectrum) where they are continually designing, deploying, trialling and improving a spectral radiometer system consisting of a frequency independent antenna, self-calibratable receivers and a broadband precision digital spectrometer. The goal is to make observations not limited by sensitivity to the systematics of the receiver used and also to the man-made Radio Frequency Interference environment.

All of the bound-bound transitions in hydrogen and helium during cosmological recombination result in spectral features in the spectrum of the relic radiation from the Epoch of Recombination and these redshift with cosmological expansion to appear at cm and mm wavelengths today. These additive photons ought to appear as 'tiny' spectral structures in the CMB spectrum, as predicted from our understanding of the physics of recombination. The Array of Precision Spectrometers for the Epoch of RecombinAtion - APSERa - is a venture to detect these recombination lines from the Epoch of Cosmological Recombination. RRI has already carried out a feasibility study for an experimental detection of these recombination lines. Researchers at RRI have proposed an algorithm to detect these tiny fluctuations buried in the sky spectrum by modelling the sky radiation emanating from Galactic and extragalactic sources. In this algorithm, for the first time, they have introduced the concept of Maximally Smooth functions that has proved capable of distinguishing the complex signal of interest against the crowded radio foreground. This applies to the global 21-cm neutral hydrogen line from both the Epoch of Reionization and Recombination. In 2015-16, progress has been made in designing a 2 GHz digital correlation spectrometer with an In-phase and Quadrature sampling scheme for the APSERa project. The new spectrometer once integrated with a simple analog chain will reach calibration preparedness. A discone monopole antenna has also been designed and tested against simulation results to be used in conjunction with the spectrometer.

Indian SWAN: (Sky Watch Array Network)

RRI has proposed the design, development and use of a wideband Sky Watch Array Network across India with the following objectives –

To facilitate and conduct searches and studies of fast (typically of sub-second duration) and slow transient radio radiation originating from astronomical sources.

To facilitate and conduct high angular resolution imaging of discrete galactic and extragalactic sources at low radio frequencies.

To train, involve and provide hands-on experience to a large number of undergraduate and postgraduate students in all aspects of the SWAN, through their direct and active participation starting from the design stage to research using the array network.

The proposed competitive coordinated network with nominally 1000 sq. m array area at each location and operation spanning a decade in frequency over 50-500 MHz will be developed in three phases.

In the first phase the plan is for a moderate setup to be attempted for realizing and demonstrating the essential features. During the year 2015-16 the focus has been on realizing a setup with 8 independent stations operating over a common narrow band, using available hardware from previous projects (a GBT receiver, MWA tiles and beam-formers). This set up is now being tested at Gauribidanur field station, following which relocation of the system to 8 different sites will be considered. Test observations will include targeted searches for radio transients in a few select directions of specific astronomical interest, and coordinated observations with the GMRT.

The implicit aim is to initiate a collective effort to develop the SWAN with many of the 40+ technology and science institutes, such as the IITs, NITs, IISERs & NISERs, as well as many universities across India. To prepare for student involvement, appropriate schools/workshops (in co-ordination with existing programs) are being arranged to formally introduce under-graduate and master's students to radio astronomy, basic concepts and advanced topics/techniques, over a few weeks each year, along with hands-on experience with systems. The first such school was conducted in June 2015 at RAC-Ooty. 11 students from IITs, IISERs, IIST, UNIs, and other colleges participated in the school. The next such school is scheduled for 2016 summer.

Ongoing Research

Ramesh Balasubramanyam's areas of current professional research interests are diffuse matter in the Milky Way and other galaxies; analog & digital signal processing; instrumentation and techniques for astronomy; brain computer interfaces & patient assistant systems.

Within signal processing, Balasubramanyam has worked on the following projects:

(i) **Forward error correcting codes (FECCs):** In collaboration with Parvathi Chandrasekaran (Research Assistant, RRI) , **Balasubramanyam** has extended his earlier simulation study (PC & RB, 2014, IETE-JoR, 61(1), 56-64), where they analysed the performance of three different FECCs, each with multiple code rates in the range 0.5 to 1, over a range of SNR of the AWGN channel for four symbol mapping schemes and two fading types, using a common MIMO-STBC-OFDM communication link, transferring data at a base rate of 100 Mbps.

During the past year they have extended this work to include Block Product Codes. These are multidimensional codes that build redundancy in orthogonal directions and thereby improve the FECC efficiency. They have completed a systematic study of 2 and 3 dimensional product codes using normal and extended Hamming codes as component codes. So far, they have used a hard-decision approach to detect and correct errors and demonstrated that building redundancy in dimensionality is better than extending the code. Their 3D hard decision decoder performs nearly as good as the AHA-TPC that uses extended 2D codes with soft decision. The work has been submitted and is under review. Their next aim to convert the hard-decision decoder into a soft-decoder to further improve performance.

(ii) **Open Voice Command Interface kit using Android:** In collaboration with Junaid Ahmed (VSP student, RRI), **Balasubramanyam** had developed an Open Voice Command Interface Kit as a continuation of his research on patient-assistant systems. An article describing the Kit, its wheelchair application and the results obtained has already been published in IEEE Transactions on Human-Machine Systems. The published kit-design uses Linux running on a Cubie-board as the system resource. To remove this dependence, this year, Balasubramanyam and his group have successfully deciphered the voice commands using Pocket-sphinx running on Android and communicated the resultant commands to steer a toy-car. They are now in the process of integrating the rest of the software architecture with this capacity to make an Open VCI using Android. Because semi-autonomous mobility is desirable, key issue here would be to measure the distance moved accurately for which stereo vision technique could be an useful tool to employ. Finding correspondence from natural scenes is another key problem and the group is working on a method that holds promise in solving this problem.

(iii) Autonomous feeding robotic arm: Collaborating with Pradeep, (VSP student, RRI) Balasubramanyam has extended his patient-assistant system repertoire to an autonomous feeding robotic arm. Prem, (VSP student, RRI) as well as Praveen (VSP student, RRI) have also worked on this project. They had completed the control aspects of the arm but the feedback part of the arm design is still pending.

Within the domain of instrumentation and techniques, Balasubramanyam and his group's contribution has been in the making of a **cm-wavelength telescope using the principle presented in the paper An Efficient Linear Array Imager for Radio Astronomy (RB, 2014, MNRAS 444, 2212).** They have developed an economical method to make light-weight, pre-loaded cylindrical panels that integrate the panel support. All panels are identical in construction though the pre-load factor determines the radius of curvature. Thus, different panels of the parabolic cylinder are realised by simply varying the pre-load factor. The current developments indicate that 1.2 m x 0.6 m panels can be realised to an accuracy of $\pm$1.5 mm rms in this process. Attempts are being made to make the panel larger, while retaining the accuracy. The group has also

installed a CMM system in the workshop at the RRI field station at Gauribidanur. The CMM system has the capacity to measure the panels to 1 mm rms accuracy. Once the panel development is completed, with a total of 16 or 32 panels, Balasubramanyam plans to measure and adjust the surface. The next step would be to attach them to the backup frame.

Balasubramanyam had also proposed a new phase switching scheme in the One Element Interferometer (RB, 2014, MNRAS 444, 2128). The principle can be adapted to measure surface deviations of a radio telescope. He also plans to demonstrate the principle using a satellite dish antenna and deploy it to search for bright galactic radio transients.

Avinash A. Deshpande's research interests lie in radio astronomy, signal and image processing, radio transients, pulsars, polarization, EoR and instrumentation. During the period 2015-16, Deshpande has been exploring the following research problems in the sphere of pulsars -

(i) **Periodicity Determination from a Sequence of Occasional Single Pulses** - It is often the case that, in a given duration of its observation, not all the pulses emitted by a pulsar are detectable. This is primarily due to intrinsic variability in the pulse intensity in addition to the relatively slower modulation caused by interstellar scintillation or, in other words, scattering and interference caused by the non-uniform interstellar medium combined with relative motion of the source with respect to the observer. While these variations in themselves are a topic of considerable interest in probing pulsar emission processes, they render pulsar searches difficult, particularly the estimation of its underlying periodicity. In cases where only a few occasional pulses are observed in a long sequence spanning hundreds of periods (as typically is the case in RRATs i.e. rotating radio-transients that are a category of pulsars), estimation of the period reliably is indeed challenging. In practice, this amounts to finding a greatest-common-divisor (GCD) for a set of intervals between pulses, estimated in turn from the arrival times of a few pulses.

To enable such estimation in an automated way, collaborating with Abhishek Som, (IISER-Kolkata) and Girish Kulkarni, (IIT-Kanpur) Deshpande has developed a novel algorithm using the fact that for N pulse-arrival times, estimates of N(N-1)/2 intervals are available, although complete non-redundancy within such a set is understandably rare. In noise-free cases, they had found that even six or so pulses, with random occurrence, suffice to reliably estimate the underlying period in most cases. However, the measured pulse-arrival times can have significant uncertainty owing to possible pulse-shape changes, and invariably due to finite signal-to-noise ratio of detected pulses. To assess the performance of their procedure in presence of noise, elaborate simulations were also performed. The simulation results show that reliability of period estimation improves, as expected, with increase in the signal-to-noise ratio, as well as with number of pulses. Further, the simulation results suggest that with 20 or more pulses, with random occurrence, the underlying period can be estimated with high accuracy even when signal-to-noise ratio may be very poor. Of course, the apparent period might also be an integral multiple of the true period, but the associated probability reduces significantly with the number of pulses when pinpointing the highest probability period becomes more and more attainable. Encouraged by these findings, a set of blind tests are also being conducted using data from real observations so as to rule out the detection of sub-integral multiples of the true period.

(ii) **Reliable measurements of off-pulse radio emission from pulsars -** During the last year, Deshpande and Kumar Raviranjan (PhD student, RRI) had assessed the existing claims of the detection of off-pulse radio emission from pulsars, and based on detailed simulations shown that extended out-of-band leakage via aliasing could result in undesired, though proportional, contribution in the off-pulse regions, increasingly so for higher DM pulsars.

In view of the potential shortcoming of the existing methods, they have explored alternative ways to detect off-pulse emission from pulsars, which would be immune to such effects. For testing their idea they have used data from Green Bank Telescope (GBT) taken using RRI-GBT Multi-band Receiver System. Then they have tested their new method on the data at

different radio frequencies and also performed simulations to establish the immunity of their approach as against the non-immunity of previous approaches.

(iii) **Search for pulsars and fast transients with Gauribidanur telescope -** A specially tuned pipeline for processing the survey data from the Gauribidanur array at 34.5 MHz is being developed by A.A. Deshpande and H.A. Aswathappa (RRI) to detectlow-frequency radio transients, including single pulses from pulsars, with particular attention being paid to reduce effects of unavoidable corruption by heavy radio-frequency interference.

Deshpande's research in the field of instrumentation during the previous year consists of

(i) **New methods of instrumental polarization calibration** - In an investigation of potential non-conventional techniques for polarization calibration of radio astronomy instruments, Deshpande and Wasim Raja (Cotton College University, Guwahati) have proposed an elegant Fourier-based method applicable for new generation telescopes that are being designed with rotation about the dish or feed axis. It is shown that the estimates made using the first two of the Fourier components provides desired cushioning against possible uncertainties in rotation angles, compared to those from a direct combination of the measurements.

(ii) **Tests and refinement of the Fast-transient detection pipelines for GALFACTS survey data** - Deshpande, Tapasi Ghosh and Chris Salter (Arecibo Observatory, NAIC, Puerto Rico, USA) have continued their concerted effort begun last year, to develop a new single-pulse-search pipeline for faster and simultaneous processing of the 7-beam data from the GALFACTS survey, so as to readily assess the possible astronomical origin of any detected dispersed single pulse during the search. The new pipeline was tested on real data (256 channels across 300 MHz bandwidth, sampled at 1 ms intervals), and feedback for the test runs is being used to reduce the false-alarm rate. As a verification of their designed pipeline, the research team has tested a set of pulses detected during processing of the test data and found them to indeed correspond with a known pulsar.

Nayantara Gupta's areas of current professional research interests are gamma rays and gamma ray bursts, cosmic rays and neutrinos.

Gupta's work in the area of gamma ray and gamma ray bursts in the last year consists of **Proton Synchrotron Radiation from Extended Jets of PKS 0637-752 and 3C 273, (ApJ 2016, 817, 6)** where she has collaborated with Wrijupan Bhattacharyya (DESY, Zeuthen, VSP student, RRI).

Many powerful radio quasars are associated with large-scale jets, exhibiting bright knots as shown by high-resolution images from the Hubble Space Telescope (HST) and the Chandra X-ray Observatory. The radio-optical flux component from these jets can be attributed to synchrotron radiation by accelerated relativistic electrons. So far IC/CMB model has been the most popular explanation for the observed X-ray emission from these jets. Recently though, the IC/CMB X-ray mechanism has been strongly disfavored for 3C 273 and PKS 0637-752 since the anomalously hard and steady gamma-ray emission predicted by such models violates the observational results from Fermi-LAT.

Gupta and Bhattacharyya in this paper propose the proton synchrotron origin of the X-ray-gamma-ray flux from the knots of PKS 0637-752 with a reasonable cap on its luminosity, by considering synchrotron radiation from an accelerated proton population. Moreover, for the source 3C 273, the optical data points near 10^{15}Hz could not be fitted using electron synchrotron. Therefore Gupta proposes an updated proton synchrotron model, including the optical data from HST, to explain the origin of the optical-X-ray-gamma-ray emission from the knots of quasar 3C 273. The model happens to be an extension of the work done by Kundu and Gupta in 2014. The results also show that TeV emission from large-scale quasar jets, in principle, can arise from proton synchrotron, which they also discuss in the context of knot wk8.9 of PKS 0637-752.

An alternative approach to explaining the observed X-ray emission from large scale jets lay in taking into account **stochastic and shear acceleration in these large scale jets of quasars**. Gupta has studied the stochastic and shear acceleration of electrons in kiloparsec scale jets of quasars. Their synchrotron emission can explain the radio-optical-X-ray spectrum

from jets of some quasars like PKS 0637-752. Thus shear acceleration of electrons could be an alternative scenario to explain the observed X-ray emission from large scale jets.

During 2015-16, Gupta's interest in neutrinos has also led her to investigate **high-energy neutrinos from the gravitational wave event GW150914 possibly associated with a short Gamma-Ray Burst** in collaboration with R. Moharana (University of Johannesburg), S. Razzaque (University of Johannesburg) and P. Meszaros (Pennsylvania State University) **[Physical Review D in press 2016].** High-energy neutrino (HEN) and gravitational wave (GW) signals can probe astrophysical sources in addition to electromagnetic observations. Multimessenger studies can reveal nature of the sources which may not be discerned from one type of signal alone. Here the authors discuss HEN emission in connection with the Advanced Laser Interferometer Gravitational-wave Observatory (ALIGO) event GW150914 which could be associated with a short gamma-ray burst (GRB) detected by the Fermi Gamma-ray Burst Monitor (GBM) 0.4s after the GW event and within localization uncertainty of the GW event. Calculating the HEN flux from this short GRB, GW150914-GBM Gupta and her collaborators show that non-detection of a high-energy starting event (HESE) by the IceCube Neutrino Observatory can constrain the total isotropic-equivalent jet energy of this short burst to less than 3 x 10^{52}erg.

Biman B. Nath's areas of professional research interests lie in galactic outflows; interaction of diffuse gas with galaxies; cosmic rays; intracluster medium.

His research within galactic outflows deals with

(i) **Modeling Fermi Bubbles** - The existence of a bright gamma ray feature rising from the centre of the Milky Way has been revealed in recent observations with the Fermi Gamma Ray telescope. This feature has been shown to be also bright in X-rays and microwave wavelengths. Although there have been attempts to explain the Fermi bubble through AGN activity of the black hole at the Galactic Centre, Nath's numerical hydrodynamical simulation shows that it can be better modelled as the effect of a galactic wind triggered by star formation at the Galactic centre. Nath's collaborators in this work were Kartick Chandra Sarkar (PhD student, RRI) and Prateek Sharma (IISc). [**Multiwavelength features of Fermi bubbles as signatures of a Galactic wind**, **Sarkar, K., Nath, B. B, Sharma, P. MNRAS,453, 3827 (November 2015)]**

(ii) **Suppression of galactic outflows** - The hot circumgalactic gas in galaxies can suppress the galactic outflows in very massive galaxies. In addition, cosmological infall of matter can also suppress the outflows. Working with Priyanka Singh (PhD student, RRI), Jasjeet Bagla (IISER Mohali) and Sandeep Rana (PhD student, IISER Mohali), Nath has studied these two effects using N-body simulations and analytical estimates, and found that galaxies more massive than the Milky Way tend to inhibit galactic outflows triggered by star formation. This has important implications for the enrichment of the intergalactic medium. [**Suppression of galactic outflows by cosmological infall and circumgalactic medium**, **Singh, Priyanka, Rana, S., Bagla, J. S., Nath, B. B., MNRAS, in press]**

(iii) **How do supernovae merge to form superbubbles? -** Superbubbles are caused by multiple supernovae in massive star clusters. Nath along with Naveen Yadav (PhD student, IISc) and Prateek Sharma (IISc) has studied this process in detail, with the help of high resolution, 3D numerical hydrodynamical simulations. They found the conditions under which multiple supernovae can merge in a way to make the pressure on the superbubble larger than equilibrium conditions with respect to the ambient medium, thus making it expand. The results can be used in simulations of galaxies which lack resolution power, and also lead to an understanding of the basic physical processes which govern the micro-physics of the formation of galactic outflows. [**Supernovae under microscope: How supernovae overlap to form superbubbles**, **Yadav, N., Mukherjee, D., Sharma, P., Nath, B. B. (Submitted to MNRAS, March 2016, arxiv: 1603.00815)]**

Diffuse X-ray emission from galaxies is Nath's topic of research within the subgroup of interaction of diffuse gas with galaxies, where he has collaborated with Kartick Chandra

Sarkar (PhD student, RRI), Prateek Sharmaand Yuri Shchekinov (Southern Federal University, Russia). The diffuse X-ray emission from star forming galaxies is mostly believed to arise from hot gas contained in galactic outflows. However this interpretation fails to explain some curious observations in which galaxies with low star formation rate have high diffuse X-ray brightness. The authors have pointed out that this is due to the fact that the hot circumgalactic gas in the galactic halo also contributes substantially to the X-ray luminosity. [**Diffuse X-Ray Emission from Star-forming Galaxies**, **Sarkar, K. C., Nath, BB, Sharma, P., Shchekinov, Y., Astrophysical Journal Letters, 818, L24 (February 2016)]**

Studying the circumgalactic medium with cross-correlations - Nath's previous work showed that the circumgalactic medium (CGM) can have small but interesting signatures in the cosmic microwave background (CMB). To make the observations feasible, Nath and his collaborators - Priyanka Singh (PhD student, RRI), Subhabrata Majumdar (TIFR) and Joseph Silk (Oxford University) extended his analysis to the cross-correlations of the SZ signal with X-ray signal from galaxies. This improves the signal-to-noise ratio of the detection and also constrains the pressure profile of the CGM and therefore also the model of star formation feedback in galaxies. [**[Probing the circumgalactic baryons through cross-correlations, Singh Priyanka, Majumdar, S., Nath, B. B., Refrieger, A., Silk, J., MNRAS, 456, 1495 (February 2016)]**

Biswajit Paul's area of research interest lies in X-ray astronomy, from the observational point of view as well as instrumentation. Whether it be software or hardware, within instrumentation, he works on design, execution, optimization and also extraction of scientific data from archival data of past and current missions.

During the past year, Paul's developmental work for the **Thomson X-ray polarimeter, POLIX**, has turned a corner. Based on the hardware development status of POLIX and its unique scientific prospects a small satellite mission XPoSat has been approved by the Indian Science Research Organization (ISRO), with POLIX as the scientific payload. The proposed time frame of 3 years for launch will give scientists a unique scientific opportunity in this new window to the high-energy astrophysics. POLIX is currently the only approved satellite mission for X-ray polarimetry in the world. During the period of this report the group has carried out the following developmental work:

(i) Calibration of the collimator: A fixture for calibration of the collimator has been made. The collimator has a special design with tapered hexagonal holes that gives a flat top response to mitigate errors arising due to coarseness in the directional locking of the satellite. The field of view and angular response of the collimator will be measured with this fixture.

(ii) Significant progress has been made in preparing and testing all components of the electronics: front end electronics of the detectors, processing electronics and common electronics. The group is now in a position to take up space qualified layout and fabrication of the engineering model of POLIX.

(iii) A new self-calibration method has been developed for position determination of the X-rays in the POLIX detectors. This method takes care of energy dependence of the calibration parameters. New software has been developed to implement this new method and have been tested extensively on detector data.

(iv) Simulations have been carried out to determine the scattering and absorption efficiency of X-rays in POLIX. Results from the simulations have been used to realistically determine the sensitivity of POLIX for polarisation measurement of X-ray sources. These results would be of great importance in fine-tuning the design and involved software so as to optimize POLIX's performance.

(v) A photoelectron polarimeter is also in the making.

Paul's team members in this effort are **P.V.Rishin, M.R.Golapakrishna and many members of EEG and MES.** Varun Bahal, (PhD student, RRI) has taken part in the development of the photoelectron polarimeter.

ASTROSAT LAXPC was launched in September 2015. Paul and his group have developed the data reduction software of the ASTROSAT-LAXPC collaboration along with the Indian Space Application Centre (ISAC), ISRO. After extensive tests, the software was delivered during 2015-16. A Payload Operation Centre (POC) is being run at RRI for the LAXPC

payload and all LAXPC data are being processed through a pipeline. Several PhD students have learnt LAXPC data reduction and are involved in developing some additional data reduction tools as well as running of the POC. Paul's group has carried out preliminary scientific analysis of LAXPC data from a large number of sources observed with Astrosat. They have also carried out simulations of the energy response of LAXPC detectors and used the ground calibration data to fine-tune the simulation. The data has then been used to create the energy response matrix of the LAXPC detectors. RRI's main effort has been to differentiate the energy response for different layers of the detectors, which will enable a unique self-calibration of the detectors.

Paul's collaborators on the LAXPC project were, Sujay Mate (PhD student, IISER Pune), Aru Beri (PhD student, IIT Ropar), Pragati Pradhan (North Bengal University), Nazma Islam, Gayathri Raman, Varun Bahal (PhD students, RRI) and Chandreyee Maitra (CEA-Saclay).

In 2015-16, Paul has made significant contributions in several studies of X-ray binaries, which constitute his area of scientific interest within X-ray astronomy.

(i) **Flares in LMC X-4:** Paul and Aru Beri (PhD student, IIT Ropar)have carried out a pulse profile evolution study of an accreting X-ray pulsar LMC X–4 during and after the large X-ray flares using data from two observatories XMM-Newton and RXTE. During the flares, the pulse profiles were found to have a significant phase offset. Investigating the pulse profiles for a long duration after the flares they have estimated the time required for the modified accretion column to return to its normal structure and the formation of an accretion stream that causes a dip in the pulse profile of LMC X–4. The work also carries out a pulse phase resolved spectroscopy in narrow phase bins using data from EPIC-PN and spectroscopically confirms the pulsating nature of the soft spectral component.

(ii) **Dips in XTE J1710-281:** Paul, Gayathri Raman (PhD student, RRI) and Chandreyee Maitra have carried out timing and spectral analysis of two Chandra and one Suzaku observation of an eclipsing X-ray binary XTE J1710-281. The X-ray light curves reveal pre-eclipse dips indicating presence of vertical structures in the accretion disk. The dip structures are found to be variable: single wide dip is seen in some orbits while there are multiple narrow dips in some other orbits. Spectral investigations are in progress to assess if the dip structures are related to the spectral states of the source. Time resolved spectroscopy of the dips has been carried out to measure the covering fraction and column density of material that causes the dips.

(iii) **Eclipse spectrum of X-ray Binaries:** Paul and Nafisa Aftab (PhD student, RRI) have carried out a study of the eclipse spectrum of low and high mass X-ray binaries using data from the XMM-Newton observatory. During eclipses, X-rays from the compact star are blocked by the companion star and only reprocessed emission from the surroundings are detected. Eclipse spectrum thus enables a study of the reprocessing medium: its geometry, extent, constituents etc. In most high mass X-ray binaries they find the eclipse spectrum to have a strong iron emission line, which they find to be much weaker in the eclipse spectrum of low mass X-ray binaries. In one of the LMXBs, from a large number of eclipse data Paul and Aftab have also studied variability of the eclipse spectrum against variability of the un-eclipsed soft and hard X-ray continuum.

(iv) **Comprehensive study of pulsar X-ray spectrum:** Paul along with Pragati Pradhan, Enrico Bozzo (ISDC, University of Geneva) and B.C. Paul (North Bengal University)have carried out a comprehensive analysis of the broadband spectrum of classical HMXBs and SFXTs using data from XIS and PIN instruments onboard Suzaku. Among the 39 sources that they have studied, 17 exhibit a cyclotron line that has been previously reported in literature. From the spectral fits of these sources with a single model fitted using a power law, with high energy cut-off and cyclotron line feature (wherever required), they studied the correlation between various spectral parameters. The finding was a variation of the cutoff energy with luminosity indicating that NS-HMXBs are divided into two branches. This division does not seem to be based on the specific nature of the system – whether it is a Be XRB or supergiant HMXB. And nor does it differentiate on the basis of the beaming patterns

characterizing their X-ray emission (as inferred from a comparison of their pulse profiles). For a subset of the sources, they also find linear correlation between cyclotron line energy and the cutoff energy mentioned earlier, thus confirming previous results obtained by RXTE and Ginga. The Suzaku data though, revealed for the first time that this linear correlation is not unique, but instead contains three different identifiable branches. They have also found an anti-correlation between the spectral index and luminosity. Unlike previous works though, they did not detect any anti-correlation between the X-ray luminosity and equivalent width of Kα lines. The equivalent width and the flux of the iron Kα line are found to be smaller in SFXTs than in classical NS-HMXBs.

Dwarakanath K.S. areas of professional research interests currently lie in HI at high z and groups and clusters of Galaxies. During the year gone by, Dwarakanath has been pursuing research on the following topics within the subtopic of HI at high z -

(i) **Gas Mass of Star-forming Galaxies at z ~1.3** Dwarakanath has collaborated with Nissim Kanekar (NCRA) and **Shiv Sethi (RRI)** for this work.The outcome of this research is the finding that most of the neutral hydrogen in the redshift range 1.18-1.34 is not contained in star-forming galaxies but instead remains concentrated in smaller galaxies. This has implications in understanding the composition and source of neutral hydrogen in star-forming galaxies at redshifts close to 1.3.

(ii) **Arp 65 interaction debris: massive HI displacement and star formation** Pre-merger tidal interactions between pairs of galaxies are known to induce significant changes in the morphologies and kinematics of the stellar and interstellar medium components. Large amounts of gas and stars are often found to be disturbed or displaced as tidal debris. These debris then evolve, sometimes forming stars and occasionally forming tidal dwarf galaxies. In the paper **Arp 65 interaction debris: massive HI displacement and star formation,2015, A&A, 584, 114, Dwarakanath** and collaborators - Sengupta (KA&SSI), Scott (IA), Paudel (KA&SSI), Saikia (NCRA) and Sohn (KA&SSI) present results from their HI study of Arp 65, an interacting pair hosting extended HI tidal debris. The method the authors employ is to map HI in a sample of interacting galaxy pairs. The Arp 65 pair is the latest member of this sample to be mapped. Then a resolved HI 21 cm line survey is carried out using the Giant Metrewave Radio Telescope. They use the HI survey data as well as available SDSS optical, Spitzer infra-red and GALEX UV data to study the evolution of the tidal debris and the correlation of HI with the star-forming regions within it. In Arp 65 what they see is a high impact pre-merger tidal interaction involving a pair of massive galaxies (NGC 90 and NGC 93) that have a stellar mass ratio of 1:3. The interaction, which probably occurred 1.0-2.5 x ~ 10^8 years ago, appears to have displaced a large fraction of the HI in NGC 90 (including the highest column density HI) beyond its optical disk. They also find extended on-going star formation in the outer disk of NGC 90. In the major star-forming regions, the HI column densities turn out to be 4.7 x ~ $10^{20}\mathrm{cm}^{-2}$ or lower. But no signature of star formation was found in the highest column density HI debris south east of NGC 90. This indicates conditions within the highest density HI debris remain hostile to star formation and it reaffirms that high HI column densities may be a necessity but not sufficient criterion for star formation.

Dwarakanath's research on groups and clusters of galaxies in the previous year consists of the following two problems -

(i) **An analysis of the halo and relic radio emission from Abell 3376 from Murchison Widefield Array observations - [2015, MNRAS, 451, 4207]. Lijo George (PhD student, RRI), Dwarakanath** and MWA collaborators, including many from RRI, have carried out multiwavelength observations of the nearby (z = 0.046) rich, merging galaxy cluster Abell 3376 with the Murchison Widefield Array (MWA). As a part of the galactic and extragalactic All-sky MWA Survey, this cluster was observed at 88, 118, 154, 188, and 215 MHz. The known radio relics, towards the eastern and western peripheries of the cluster, were detected at all the frequencies. The relics,

with a linear extent of 1 Mpc each, are separated by 2 Mpc. combining the current observations with those in the literature; they have obtained the spectra of these relics over the frequency range 80-1400 MHz. The spectra follow power laws, with indicies -1.17 ± 0.06 and -1.37 ± 0.08 for the west and east relics, respectively ($S \sim \nu^{\alpha}$). Assuming the break frequency to be near the lower end of the spectrum they estimate the age of the relics to be 0.4 Gyr. No diffuse radio emission from the central regions of the cluster (halo) was detected. The upper limit on the radio power of any possible halo that might be present in the cluster is a factor of 35 lower than that expected from the radio power and X-ray luminosity correlation for cluster haloes. The conclusion thus would be that the cluster halo is very extended (> 500 kpc) and/or most of the radio emission from the halo has decayed. The current limit on the halo radio power is a factor of 10 lower than the existing upper limits with possible implications for models of halo formation.

(ii) **A study of diffuse radio sources and X-ray emission in six massive clusters – [2016, MNRAS submitted]** The goal of the present study is to extend our current knowledge of the diffuse radio source (halo and relic) populations to z> 0.3. In this study, **Dwarakanath, Viral Parekh (Postdoctoral fellow, RRI),** Ruta Kale (NCRA) and Huib Intema (Leiden University, Netherlands) report GMRT and EVLA radio observations of six galaxy clusters taken from the MAssive Cluster Survey (MACS) catalogue to detect diffuse radio emission. Using archival GMRT (150, 235 and 610 MHz) and EVLA (1400 MHz) data the group made images at multiple radio frequencies of the following six clusters - MACSJ0417.5-1154, MACSJ1131.8-1955, MACSJ0308.9+2645, MACSJ2243.3-0935, MACSJ2228.5+2036 and MACSJ0358.8-2955. They could detect diffuse radio emission (halo or relic or both) in the first four clusters while in the last two clusters they do not detect any diffuse radio emission putting stringent upper limits on their radio powers. They also use archival Chandra X-ray data to carry out morphology and substructure analysis of these clusters. They find that based on X-ray data, these MACS clusters are non-relaxed and show substructures in their temperature distribution. The radio powers of the first four MACS clusters are consistent with their expected values in the Lx−P1.4 plot. However, they found an ultra-steep spectrum radio halo in the MACSJ0417.5-1154 cluster and its radio power is 5 times lower than that expected. The remaining two clusters whose radio powers are 40 times below the expected values are most likely to be in the off-state as has been postulated in some of the models of radio halo formation.

Radio galaxy morphologies and galaxy environments are Lakshmi Saripalli's current areas of research interest. Collaborating with David Roberts (Brandeis University, USA), Sanjay Bhatnagar (National Radio Astronomy Observatory, USA), **Mayuri Sathyanaryana Rao (RRI)** and **Ravi Subrahmanyan (RRI)**, **Saripalli** has explored a unique sample of 52 radio galaxies selected for their low axial ratios (length to width ratio) where she enquired into the origins of radio emission far off the axis (along which the central black hole-accretion disc combination or the central engine of the radio galaxy produces jets). The group is gathering data in total intensity and polarization of the whole sample of 99 low axial ratio radio sources from 46 hour radio continuum observations at two frequencies (L-band: 1-2 GHz and S-band: 2-4 GHz) in two array configurations of the JVLA telescope. Of this 56 radio sources have already been observed and plans continue for the remaining 43 such radio galaxies. The ultimate goal of the observations is to investigate into

(1) Which sources have undergone radio axis change and into the causes of radio axis changes
(2) Origin of the enigmatic X-shaped radio galaxies by assessing the role of various plausible causative processes and
(3) For making a more detailed study of host-galaxy halos than possible before.

Saripalli has also been pursuing a select sample of 9 radio galaxies from the above original sample of 99 radio galaxies (characterized by low axial ratios) with David Roberts to obtain milli-arcsecond resolution radio continuum observations of their central radio cores. Analyzing data culled from the European VLBI Network (EVN) **Saripalli** and Roberts are well on their way to searching for cores and jets that are currently active at the centres of the radio galaxies in order to decipher the origin of their enigmatic large-scale X-shaped radio structures. The 9 observed sources have all been chosen

for their clear X-shaped structure as shown by the data from Saripalli and Roberts' earlier work in 2015 where they had imaged 52 radio galaxies (*Roberts et al, 2015*).

With the availability of low frequency images of the southern sky mapped with the Murchison Wide-field Array (MWA) **Saripalli** has embarked on **a comparative study of structures of radio source at low frequencies with their counterparts in images obtained at high frequencies**. Given the different spectral indices as well as the evolution of the observed synchrotron spectrum of different components of radio sources (for example components such as the compact radio cores, hotspots as against the more diffuse and extended lobes) such a comparison in structures across a wide frequency range is expected to reveal the true extent of radio sources (previously unseen at higher frequencies) or reveal features that are relic and therefore, again unseen at higher frequencies.

Working alongside Santosh Harish (VSP student, RRI), Ravi Subrahmanyan (RRI) and Natasha Hurley-Walker (Curtin University, WA, Australia) **Saripalli** has used the exquisite images from the ATLBS radio survey (Subrahmanyan et al, 2010; Saripalli et al, 2013) obtained at 1.4 GHz over 8.4 square degrees of the sky region and compared the radio sources with the MWA image of the same sky region obtained at the low frequency of 192.5 MHz mean frequency. They have examined the radio images and compared the source detection, morphologies and spectra over the wide frequency range covered by the ATLBS and the MWA. They have then used the r-band optical image of the same region they had investigated in an earlier work and thereby supplemented information on the detected and undetected radio sources between the two radio images. The work is complete and is in the process of internal review among collaborators.

Mayuri S. areas of professional research during the year 2015-16 were phenomenological foreground modeling for long wavelength radio astronomy, application of Maximally Smooth functions for foreground subtraction in Epoch of Reionization data, high level system design for prototype element of APSERa, detection of the 2p-2s fine structure line of Hydrogen and study of X-shaped radio galaxies.

Interest in long wavelength astronomy has been renewed due to growing interest in detecting signatures of the Epoch of Reionization at long wavelengths. However a major challenge in detecting this cosmological signal is the presence of foregrounds that are orders of magnitude brighter. At long wavelengths the strongest foreground is presented by emission from our own Galaxy. Although traditionally these foregrounds are modeled as a power law owing to the dominating synchrotron emission, this is a rather simplistic assumption. There exist global sky models that present a data driven method to simulate the low frequency sky, however they are not necessarily physically motivated. Collaborating with **Ravi Subrahmanyan (RRI)**, **N Udaya Shankar (RRI)** and Jens Chluba (Johns Hopkins University / IoA Cambridge), **Rao** presents a **physically motivated or phenomenological global sky model** that incorporates break in the synchrotron spectrum, free-free emission as well as populations of sources with different spectral indices. The inputs to the model are data from all sky-maps at 150 MHz, 408 MHz, 1420 MHz and 23 GHz, as well as maps at 22 MHz and 45 MHz from available global sky models, to provide a constraint at lower frequencies. Having generated a code that does a best fit to the aforementioned input maps, parameter values are narrowed down and the group's model can then be used to generate all sky maps and sky spectra between 10 MHz to 23 GHz with a resolution of 5 degrees.

A challenging problem in astronomy sometimes involves recovering a weak spectral feature from a sky spectrum, which has contaminants from Galactic and extragalactic continuum emission that is several order of magnitudes larger than the signal of interest. Earlier, **Rao** and her collaborators, **Ravi Subrahmanyan (RRI)**, **N Udaya Shankar (RRI)**and Jens Chluba had arrived at a method of using 'maximally smooth' functions to carefully fit to the foreground and the CMB such that any cosmological recombination signal can be extracted without being fitted out by a fitting function. During the last year, the group has extended the application of the maximally smooth functions to distinguish between the **complex foregrounds and the redshifted global 21cm signal** arising from the Epoch of Reionization**.** The radio foregrounds are expected to be smooth over the bandwidth of the predicted EoR signal (~10-200 MHz). However the functional form of the foreground spectrum is not known to the precision required so as to be modeled exclusively. Using polynomials of high order to model the foreground as has been described in literature could result in potentially losing a significant fraction of the EoR signal. The group has shown that adopting maximally smooth functions preserves the EoR signal while clearly fitting the foreground alone, for the vanilla global EoR signal. There is no loss in signal when

the order of these smooth functions is increased to any arbitrarily high value.

APSERa – Array of Precision Spectrometers for the Epoch of Recombination is a radio astronomy instrumentation project that **Rao** is involved in together with **Ravi Subrahmanyan**, **N Udaya Shankar**, **K S Srivani**, **B S Girish**, **A Raghunathan**, **Somashekar (all at RRI)**, **Saurabh Singh (PhD student, RRI)** and Jens Chluba. During the last year progress has been made in designing a 2 GHz digital correlation spectrometer with an In-phase and Quadrature sampling scheme. A simple analog chain design will now be integrated with the digital system to work out calibration methods for the receiver. A discone monopole antenna has been designed and tested, and found to be matching the simulations, but issues like the effect of ground temperature pick up are yet to be addressed. An ADC calibration scheme has also been formulated and is in the testing phase.

The **2p3/2 to 2s1/2 fine structure line of atomic Hydrogen at 9.9 GHz** could potentially serve as an important diagnostic of radiative transfer in star-forming regions. More importantly, the line transition may be developed to be a probe of cosmological reionization during the epoch of reoinization (EoR), complementary to the redshifted 21-cm line. Detection of the 2p-2s line faces some problems that are similar to those in detection of the weak ripple like signals from the recombination epoch. The fine-structure transition itself is a blend of hyperfine lines and is expected to be a weak and extremely broad feature, making detection challenging. Moreover, this line transition has never been detected outside the solar system. Predictions of the line strength and distribution in HII regions and in the cosmological context are also uncertain owing primarily to poor knowledge of the relevant radiation background. Rao and her collaborators **Ravi Subrahmanyan (RRI)**, Juergen Ott (National Radio Astronomy Observatory), Frank Briggs (Mount Stromlo Observatory, ANU) are currently involved in observing carefully a select variety of high emission measure Galactic HII regions for a first detection with moderate spatial resolution. The strength and nature of the line feature is inherently dependent on the Ly-alpha and field and physical parameters of the HII regions, such as their emission measure and ionization fraction. Detection and imaging together would be the best probe to understand the physics of the radiative transfer, ionization equilibrium and dust absorption.

Rao has also been studying **X-shaped radio galaxies** with **Lakshmi Saripalli (RRI)** and other collaborators.

Sridhar S' areas of professional research interests are exoplanetary dynamics and stellar dynamics in galactic nuclei.

Collaborating with Jihad Touma (American University of Beirut, Lebanon), **Sridhar** presents a three-part report on the nucleus of the Andromeda galaxy. There is considerable evidence that the nucleus of the Andromeda galaxy has a dense, eccentric and lopsided disc of stars orbiting a massive black hole. The case for a massive black hole at the galactic centre is even stronger, because the motions of some individual orbiting stars have been directly observed. The structure of the dense star cluster surrounding the black hole though is less clear, but it is believed to have warped and inclined components. Sridhar's aim is to understand the structure and origins of the large N (say, N = million) stellar systems orbiting within the sphere of influence of the massive black holes in the galactic centre and nucleus of Andromeda. Work over the past two decades has suggested the exciting possibility that both dynamical and statistical mechanical processes may give rise to broken symmetry states, which could be eccentric and lopsided, inclined and warped, with or without figure rotation. Although a lot of work has been done, there is no general theory of the long-term (or secular) evolution of self-gravitating star clusters.

During the year 2015-16 **Sridhar** and Touma have been engaged in a three-part work that aims at providing firm foundations for the dynamical and statistical mechanical theory of Keplerian stellar systems (whose mass M is smaller than the mass M_b of their black holes). The mass ratio $\varepsilon = (M/M_b)$ is a natural small parameter that quantifies a separation of times scales: the fast Kepler orbital times and the secular time scale which is longer by a factor $(1/\varepsilon)$. In Part I of the work, Sridhar et al. formulate the theory describing secular collisionless dynamics. Building on this, Sridhar and Touma present in Part II a statistical mechanical theory of Resonant Relaxation (RR) based absolutely on first priniciples. The RR theory is then applied in Part III to the evolution of an axisymmetric stellar disc orbiting a massive black hole.

Secular Collisionless Theory: [Stellar Dynamics around a massive black hole I: Secular collisionless theory, **S. Sridhar** and J. R. Touma Monthly Notices of the Royal Astronomical Society doi: 10.1093/mnras/stw542] the stellar system is described by a distribution function (DF) in 6-dim phase space, obeying the collisionless Boltzmann equation (CBE).

Resonant Relaxation: [Stellar Dynamics around a massive black hole II: Resonant relaxation, **S. Sridhar** and J. R. Touma Monthly Notices of the Royal Astronomical Society, doi: 10.1093/mnras/stw543] The authors present a first-principles theory of Resonant Relaxation (RR), by extending Gilbert's general theory of collisional evolution to include the Keplerian field of a black hole, and then specializing to a self-gravitating Keplerian stellar system. The authors find the interplay of secular dynamics and non-equilibrium statistical mechanics in the evolution of Keplerian stellar systems for them to reach secular thermodynamic equilibria, and set the stage for applications to the RR theory to axisymmetric discs in Paper III.

Resonant Relaxation of Axisymmetric Discs: [Stellar Dynamics around a massive black hole III: Resonant Relaxation of Axisymmetric Discs, **S. Sridhar** and J. R. Touma Monthly Notices of the Royal Astronomical Society, Submitted (preprint available on arXiv: 1602.05763)] In this paper the authors apply the theory of Paper II to the evolution of an axisymmetric stellar disc orbiting a massive black hole. Explicit formulae are derived for the loss cone rates of the stellar disc at which it loses its mass, energy and angular momentum to the black hole.

Shiv Sethi's research interest and expertise is in cosmology. During the past year, he has explored the following problems in the broad area of cosmology:

(i) **EoR detection using MWA**: In collaboration with **Sourabh Paul (PhD student, RRI)** and the International MWA EoR team, which includes several RRI scientific staff, Sethi is currently analysing MWA tracking and drift scan data, i.e., data recorded by keeping the telescope pointed at one direction of the sky and allowing the sky to drift with the rotation of the Earth during observation and also doing simulations to understand the results. They have recently completed the development of a pipeline to analyse 3 hours of raw tracking data from MWA and compared these results with simulations of noise and foregrounds to address the issue of separation of foregrounds from the EoR signal. The paper has been submitted to the collaboration review. The pipeline could be used to analyse 3 hours of such raw data under any observation condition.

(ii) **Impact of alternative models of dark matter on HI distribution at high redshifts:[The effects of the small-scale DM power on the cosmological neutral hydrogen (HI) distribution at high redshifts, Sarkar, A., Mondal, R., Das, S., Sethi, S., Bharadwaj, S., Marsh, D. J. E., 2016, JCAP, 04, 012]** Many models of dark matter predict lower values of the dark matter power spectrum at small scales as compared to the ΛCDM models. **Abir Sarkar (PhD student, RRI),** Subinoy Das (IIA), Rajesh Mondal and Somnath Bharadwaj (IIT- KGP) and David Marsh (King's College, London) and **Sethi** study the impact of two such classes of models — Late forming Dark Matter (LFDM) and Ultra Light Axion (ULA) — on the HI (neutral hydrogen) distribution at large redshifts. In particular, they study the evolution of HI mass density in the redshift range $2 < z < 5$ and the HI signal from the Epoch of Reionization (EoR). Using simulations, they have showed that the HI power spectrum gets enhanced by a factor of 2 – 10 in such models, and could thus become a potential test of such models. They have also shown that the combined constraints from these two cosmological probes based on HI distribution yield comparable or better constraints as compared to other observables in the above redshift range.

(iii) **2p–2s maser as a probe of first black holes: [3-cm Fine Structure Masers: A Unique Signature of Supermassive Black Hole Formation via Direct Collapse in the Early Universe, Dijkstra, M., Sethi, S., Loeb, A. 2016, ApJ, 820, 10**]. The fine structure line of neutral hydrogen (2p–2s transition, wavelength = 3:04 cm) can provide a probe of primordial black holes. Such black holes could form by direct isothermal collapse which provides an ideal setting for 2p–2s masers which are nothing but lasers emitting radio waves. **Sethi**, Mark Dijkstra (Oslo University) and Abraham Loeb (Harvard University) show that in such cases CMBR can amplify by a factor of up to 10^5. Such masers could have fluxes in the range 0.3–3 μJy which are detectable by ultra-deep surveys using the upcoming radio interferometer SKA1-MID.

(iv) **Gas mass of star-forming galaxies at z ≈ 1.3: [The Gas Mass of Star-forming Galaxies at z ≈1.3, Kanekar, Sethi, Dwarakanath, 2015, ApJL, 818, 28]** for this work **Sethi** has collaborated with Nissim Kanekar (NCRA) and **K. S. Dwarakanath (RRI).** Sethi reports a Giant Metrewave Radio Telescope search for HI 21 cm emission from a large sample of massive star-forming galaxies in the redshift range 1.18-1.34, lying in sub-fields of the DEEP2 Redshift Survey. The search was carried out by co-adding (stacking) the HI 21 cm emission spectra of 857 galaxies, after shifting each galaxy's HI 21 cm spectrum to its rest frame. This allowed Sethi et al. to reach an unprecedented noise level of 2.5 μJy in the co-added spectrum at a velocity resolution of 315 km s^{-1}. This yields the 3σ constraint MHI < 2.1 $x10^{10}M_{\odot}$ for an assumed line width of 315 km/s on the average HI mass of the 857 stacked galaxies, the first direct constraint on the atomic gas mass of galaxies at z> 1. The implied limit on the average atomic gas mass fraction (relative to stars) is Mgas / Mstar < 0.5, comparable to the cold molecular gas mass fraction in similar star-forming galaxies at these redshifts. The authors find that the cosmological mass density of neutral atomic gas in massive star-forming galaxies at z ~ 1.3 is $\Omega_{gas} < 3.7\ x10^{-4}$, significantly lower than Ω_{gas} estimates in both galaxies in the local universe and damped Ly absorbers at z ≥ 2.2. The results imply that most of the neutral hydrogen in the redshift range of interest is not contained in star-forming galaxies but instead remains concentrated in smaller galaxies.

LIGHT AND MATTER PHYSICS

Overview

Members of the Light and Matter Physics (LAMP) group at RRI are pursuing research in an area of light-matter interaction which is a combination of Atomic, Molecular and Optical (AMO) physics on one hand, and intense laser produced plasmas on the other. Light-matter interactions are being investigated by this group in both classical and quantum domains using experiments as well as numerical and theoretical analysis. The interactions are studied at very high plasma temperatures, room temperature, and at extremely low temperatures attained through laser cooling methods. The use of light from the highest energy densities to the single photon regime allows an impressive range of energy scales to be investigated.

The research of the LAMP group stresses on demonstration of quantum logic using ultra-cold atoms loaded in optical lattices and various nano-traps, investigation of transport and localization properties of light in various random media, ultrafast laser induced plasmas from solid targets, nonlinear optical properties of nanomaterials, laser cooling and trapping of atoms, cold collisions, ion trapping, atoms in cavities, response of cooled atoms to external fields, quantum optics with neutral atoms and non-classical light sources, quantum walk of light, manufacture of single photon sources based on spontaneous parametric down-conversion and their applications to fundamental tests of quantum mechanics, quantum information and computing and quantum communication, quantum simulation of condensed matter physics using degenerate gases, and precision measurements. Currently, quantum logical gates are being designed by tailoring the internal degrees of freedom of quantum optical tools in external potentials.

Current Research Interests

Electromagnetically Induced Transparency (EIT)

EIT is a quantum mechanical phenomenon where, under specific conditions, absorption line of a material can be cancelled, changing it from opaque to transparent at that particular frequency. EIT can be observed when two highly coherent lasers are tuned to interact with three or more quantum states of a material. A concerted effort is on at RRI to understand this phenomenon both from a theoretical and experimental point of view. The LAMP group has recently expanded its horizons within EIT to address one of the unique features of the quantum optics behind EIT – coherent, non-linear atom-optics in the low intensity regime. Due to elimination of linear order susceptibility by quantum interference, in EIT systems with very low intensities it becomes possible to induce higher-order interactions.

Quantum Optics

Quantum optics is a field of study in physics that applies quantum mechanical tools to understand phenomena involving light and its interaction with matter. Major fields of interest in quantum optics include manipulation of elemental particles like atoms, ions and molecules and the use of quantum optics to build further upon our current understanding of quantum information. Quantum coherence transfer between atoms and light and creation of new quantum states of light and matter are some of the other questions being actively pursued at the moment. For this purpose, experiments have been done involving a phase controlled, high-contrast non-linear switch in an atomic Delta system where Rubidium atoms (^{85} Rb), which can interact with both optical and microwave frequencies, form the system in question and the phenomenon of EIT is utilized to achieve the transfer of quantum correlations.

Another line of quantum optics research in LAMP focuses on the optical gain and enhancement from atom-optical-microwave interaction in a Delta system. Although line-narrowing has already been observed by the group, they are in the process of establishing true gain in this system by explicit measurements of input and output optical fields. A third application oriented study that the group is engaged in currently is that of finding non-Markovian signatures in atom-light interaction in a V-level atomic configuration and their possible relevance to light absorption in photosynthesis.

A preoccupation of quantum effects in light and matter has naturally led the LAMP group to explore some foundational questions in quantum mechanics. One such area of current interest is the area of Quantum measurements, which refer to measurements on a quantum system made by a measuring device, while causing very little perturbation to the system. Weak measurements through non-Hermitian operators being studied both theoretically and experimentally by the group in various systems, for example via analysing the interference pattern from a Marc-Zehnder interferometer.

Laser Cooling and Trapping

Laser cooling and trapping is a technique that has gained huge popularity throughout the world of physics in the last decade. Presently, atoms can be cooled to extremely low kinetic temperatures (150 microK) and trapped for a time period of the order of seconds. There are some techniques to cool and trap atoms of alkaline elements, the most common one being Doppler cooling. In Doppler cooling, three mutually perpendicular laser beams are made to intersect at the centre of a chamber while a pair of magnetic coils produces a magnetic field that is zero at the centre of the chamber but increases radially outwards. Tuning the wavelength and polarization of the laser beams, atoms can be cooled by repeated absorption and emission of light, and trapped by an inward force arising out of the combination of the laser beams and the spatially varying magnetic field. In other words, Doppler cooling involves a Magneto Optical Trap (MOT). Electromagnetically induced transparency and related phenomena and nature of fluctuations in a collection of cold atoms are being studied at the Laser cooling lab. An important experiment currently being conducted at RRI using a MOT is that of time-delayed intensity-interferometry of emission from laser-cooled atoms.

Hybrid Trapping Of Atoms and Ions

A hybrid trap experiment is one which combines cold atoms, ions and molecules and studies their interaction to great accuracy. Research at RRI has overturned long held views on the nature of energy transfer in the interaction of trapped ions with trapped atoms. Collision rates between atoms and ions have been accurately measured. Ion molecule and ion atom processes in hybrid traps are also being investigated by the LAMP group at a very fundamental level and a rich variety of phenomenon are being studied. The experimental realization of a dark MOT has succeeded, where the cold MOT atoms are in a specific quantum state (ground state). This state control enables state specific collision of ions with the atoms. On the other hand, for bright MOT atoms ion collision rates yield information on atoms in a mixture of ground and excited states. The difference in these two collision rates would give the collision rate with atoms in the excited state. Precise experimentally viable strategies to achieve a trap system that can carry forward an ion-atom system to the quantum collision limit have been formulated. Collisional cooling of light ions such as $^{39}K^{+}$ by co-trapped heavy atoms such as ultracold neutral ^{85}Rb atoms has been achieved recently by the LAMP group. Most recently, the group has also experimentally realised the direct photodissociation of trapped Rb_2^{+} molecular ions in the presence of cooling light for the Rb magneto-optical trap (MOT). This apart, another problem of current interest is the state selective collision rate measurement in ion-atom mixtures in a hybrid traps.

Cavity Physics and Cavity QED

Hybrid trap experiments, as mentioned above, can access the quantum electrodynamic regime for atom-electromagnetic field interactions. Using cold ions, atoms and molecules simultaneously cooled and trapped with photons in a high Q optical cavity, the non-classical nature of atom-field interactions are being tapped. This is the first such experimental set-up of its kind and provides a complete system for the study of cold dilute classical and quantum gases.

An optical Fabry-Perot cavity built around a spectroscopy cell containing enriched rubidium vapour acts as the stage for one of the initial experiments. Light resonant with a specific ^{87}Rb transition is controlled by the transverse intersection of the cavity mode by another resonant light beam. Negative logic switching through destruction of transmitted light intensity and positive logic switching through a build-up of cavity mode intensity, using light as a control, has been demonstrated. Such an All-Optical-Switch (AOS) is a key component for computing architectures with photons and has the possibility for many practical applications.

The working of the switch has been theoretically understood and experimentally implemented. The prospects for working with this switch with two-, three- and four-level atomic systems provide robustness for the practical implementation of the switch and show the direction for significant improvement of the switch.

Light Propagation in Random Media

Multiple scattering of light in random media, like fog, reduces visibility because propagation of light in random media is diffusive rather than ballistic. This in turn leads to some interesting phenomena like mirrorless lasing, Levy statistics and weak and strong localization. Experiments using colloidal suspensions of dielectric or magnetic microspheres, both active and passive, as well as Monte Carlo simulations and theoretical analyses are the different methods being employed to probe this process of light propagation. For the case of real-time imaging through fog, the LAMP group at RRI has successfully imaged through strongly scattering media in real-time, obtaining images at rates faster than the critical flicker frequency of the human eye, so that the images are perceived as continuous. This is an important breakthrough in the design of continuous, flicker-free display devices that can aid navigation under poor visibility.

Fundamental Tests of Quantum Mechanics Using Quantum Optics Based Tools

Quantum mechanics is a cornerstone of modern physics. Just as the 19th century was called the Machine Age and the 20th century the Information Age, the 21st century promises to go down in history as the Quantum Age. However, can we really claim to fully understand quantum mechanical principles? How much do we really believe of what we know? Answers to such questions require us to revisit the fundamental postulates of quantum mechanics and perform precision theoretical and experimental investigations to come up with the right bounds. In the LAMP group, a part of the focus is to attempt such investigations using single light particles i.e.

single photons as tools. Such tests are important in the current theoretical physics scenario where there is substantial interest in unification of quantum mechanics and general relativity. Such unification attempts would also be benefitted if one can have a more precise understanding of the principles involved in at least one of the theories, i.e., quantum mechanics.

A major result in this field from the LAMP and TP groups combined has been a more complete understanding of the limitations of a naïve application of the superposition principle in slit based interference experiments. Boundary conditions for the wave function in the three different scenarios of having both slits open and the two individual slits open one at a time are different and as such superposition principle should not be directly applicable in this case. In the recent work by the LAMP group, researchers have used the Feynman path integral formalism to quantify contributions from non-classical paths in quantum interference experiments in terms of the normalized Sorkin parameter termed as "kappa". The work provides a theoretical bound on this quantity and implies that experimental realisations of non-classical paths in slit based table top interference set ups are very much possible.

In a more recent work on the same concept, researchers from the LAMP group along with collaborators from the Indian Institute of Science have come up with an analytic formula for the Sorkin parameter. The analytic formula makes the experimental demonstration easier as the parameter dependencies on different experimental quantities can now be estimated. They have also shown beautiful overlap between results obtained from their analytic formula and those obtained using much more resource intensive Finite Difference Time Domain simulations. Experimental verification of this work is currently under execution in the LAMP lab using both infra-red and microwave optics based tools.

Quantum Information and Quantum Computation

The main thrust here is research on experimental and theoretical aspects of quantum information and quantum computation. The systems of choice are qutrits (three dimensional quantum systems), based on spatial degrees of freedom of the single photon. The LAMP Group has been one of the first labs in the country to develop the technology of entangled and single photon sources, both Type I and Type II, based on spontaneous parametric down conversion in bulk non-linear crystals. The single photons and their various degrees of freedom are used to investigate aspects of quantum optics, quantum information and quantum computation. Photons are massless, chargeless particles and as such perfect for communication purposes. In the near future, the LAMP Group wishes to enter the domain of quantum communication and develop both terrestrial and satellite based technologies.

Nonlinear Optics

Nonlinear optical (NLO) transmission of materials finds applications in optical switches, optical limiters and saturable absorbers. Materials show tunable, enhanced characteristics in the nano phase, which can be very different from their properties in the bulk form. Optical nonlinearities of novel nanoparticles and nanocomposites are being investigated in the LAMP group. Ultrafast (100 fs) and short (5 ns) laser pulses are employed to identify features of nonlinearity in different time domains, employing the techniques of Z-scan, four wave mixing and pump-probe spectroscopy. In addition to demonstrating prototype NLO devices like mesoscopic nanocarbon based optical diodes and novel blue light emitting truxene discotic liquid crystals, these investigations have also thrown new light into the role of lattice defects in determining the nonlinear absorption behaviour of novel materials like nine-atom silver quantum clusters (QCs), graphitic carbon nitride (GCN), reduced graphene oxide (rGO) nanosheets, Ag2S-CuS nanocomposites, CdO nanomorphotypes, and a few other systems. In another work of far-reaching importance for graphene based electronics, the LAMP group has experimentally proved an impairment of electron mobility in doped-graphene due to increased electron-defect scattering. Employing a variety of techniques such as Raman spectroscopy, ultrafast spectroscopy, nonlinear transmission measurements and density functional theory, it has been shown that the graphitic dopant configuration is stable in graphene and does not significantly alter electron–electron or electron–phonon scattering (which is otherwise present in doped graphene) by preserving the crystal coherence length.

Laser Induced Plasmas

Plasma, the fourth state of matter, is routinely produced in the LAMP labs by irradiating suitable targets with powerful pulsed lasers. These plasmas which exist only for a few microseconds can be considered as short-

lived stars, and their study is often called 'Laboratory Astrophysics'. Ultrafast laser produced plasmas ejected from metal targets (Nickel, Zinc and Aluminium) irradiated in vacuum are found to contain electrons, ions, visible radiation, and high energy photons in the soft and hard X-ray regimes. Spectroscopic investigation of the plasma can be used to identify constituent elements of an unknown target. Temporal evolution of the plasma studied using time of flight techniques in the nanosecond regime gives information on the velocity, acceleration and recombination rates of the constituent ions, electrons and neutrals (recombined ions).

Quantum Simulation of Condensed Matter Problems Using Degenerate Gases

A new experiment facility is being set up by the LAMP group towards creating a Sodium-Potassium gas mixture at nano-Kelvin temperature. At this very low temperature well below critical temperature for Bosonic species and Fermi temperature of Fermionic species, the behaviour of the trapped cloud can be completely described by quantum theory and thermal fluctuations can be ignored. The system would then be a model system for investigating purely quantum mechanical phenomena that are analogues for complex condensed matter physics questions such as unconventional superconductivity, disordered-interacting phase diagrams etc.

Saptarishi Chaudhuri's research focus is in the area of ultra-cold atoms and molecules in optical and magnetic traps, quantum simulation of condensed matter physics using degenerate gases, and precision measurements.

Chaudhuri and his group are setting up a new experimental facility in the Institute towards creating a Sodium-Potassium gas mixture at nano-Kelvin temperature. At this very low temperature well below critical temperature for Bosonic species and Fermi temperature of Fermionic species, the behaviour of the trapped cloud can be completely described by quantum theory and thermal fluctuations can be ignored. Therefore, the system can be an ideal test bed for investigating purely quantum mechanical phenomena that are the starting point for looking into complex condensed matter physics problems such as unconventional superconductivity and disordered-interacting phase diagrams, to name only a few. As a long term goal, the set-up will also evolve to produce quantum degenerate ground state molecules with a permanent electric dipole moment. These molecules can in turn be trapped in periodic potentials created by interfering trapping light and the magnitude of the effective dipole moment can be manipulated using external electric fields. Therefore, effects of true long-range interactions in quantum gas can be investigated.

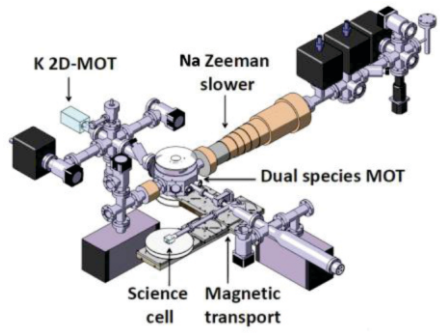


Fig 1: A schematic diagram of the planned experimental set-up to produce NaK quantum gas mixture using laser cooling techniques

Andal Narayanan's areas of professional research interests currently include quantum optics with atoms and light, quantum weak measurements in atom-quantum-optical systems, non-Markovian signatures in atom-light interaction and their possible relevance to dynamics of light harvesting complexes in photosynthesis.

Under the broad research topic of quantum optics, Narayanan has been trying to demonstrate the underlying physics in the following problem: **A phase controlled, high-contrast non-linear switch in an atomic Delta system** - Narayanan's collaborators in this project are Megha Ghosh (VSP student, RRI, awaiting admission at University of Michigan), Asha K (Joint PhD student, RRI, Kuvempu University), **Ayyappan Jayaraman (PhD student, RRI)**, Barry Sanders (IQST, Calgary, Canada) and Fabien Bretenaker (Laboratoire Aime Cotton, Orsay, France). The strong point of the research done by this group has been in ways to efficiently transfer quantum correlations, which are quantum signatures in atom-light interaction, from one frequency domain to another. In particular, the group uses Rubidium atoms (^{85} Rb) that can interact with both optical and microwave frequencies and utilizes the phenomena of Electromagnetically Induced Transparency (EIT) to achieve this transfer. The

transfer variables can be encoded in intensities, phases and intensity fluctuation statistics of optical and microwave fields. With this background, the group's research activities during the last year was aimed at demonstrating an intensity switch in the optical domain, operating at low optical intensities, that is controllable by a parameter in the microwave domain.

Using a high quality factor microwave cavity, Narayanan and her group generated a strong drive magnetic field inside the cavity. This induced higher order interaction of atoms with the optical coupling field (w_c) and the drive magnetic field (w_m). A sum frequency was generated at the optical probe field frequency (w_p), which underwent strong two-photon absorption. Compared to traditional non-linear optical processes this sum frequency was generated at much lower strength of coupling and drive field intensities due to the elimination of linear absorption because of EIT effect.

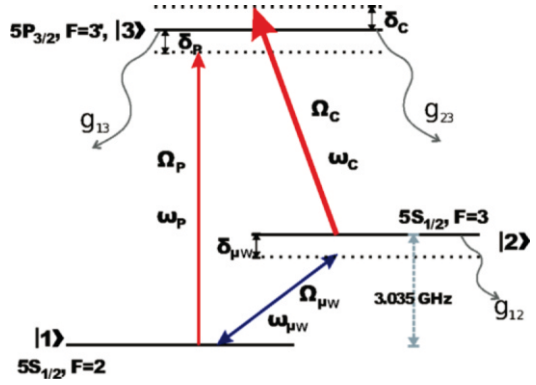


Figure 1

The group then successfully demonstrated a high-contrast change in intensity in the optical domain when the phase of the microwave field was changed by a value p. This phase is the quantum phase difference between the ground hyperfine states |1> and |2> seen above in Fig. 1, of ^{85} Rb. This means that a simple phase change in the microwave domain is acting as an intensity switch in the optical domain.

The successful realization of this experiment has led to future plans of demonstrating a reversal of this phenomenon. Or, in other words, imparting a quantum phase change in the microwave domain should also be possible by manipulating the ^{85} Rb properties in the optical domain.

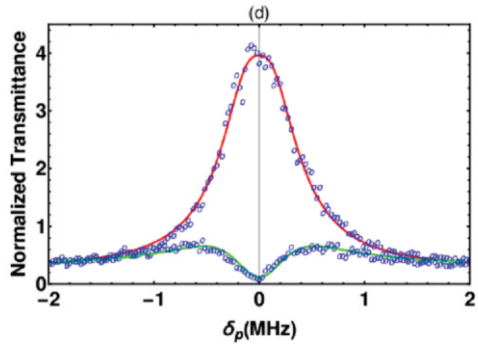


Figure 2

Under the theme of Quantum weak measurements in atom-quantum-optical systems is Narayanan's work on **optical gain and enhancement from atom-optical-microwave interaction in a Delta system.** Narayanan's collaborator in this project is Asha K. (Joint PhD student, RRI, Kuvempu University). Because of the observed higher strength of interaction of the Delta system with the magnetic field at microwave frequencies the group has tried to establish experimentally that true gain in the optical probe field (w_p) of a Delta system is possible. What they expected to see was line narrowing – a hall-mark signature of gain. As shown in Fig. 3 below, the experiment shows that the line width of the optical probe that is exiting after interaction with ^{85}Rbatoms along with optical coupling and microwave probe field, narrows by more than 50 % (blue) compared to the probe field when the microwave field is absent (yellow).

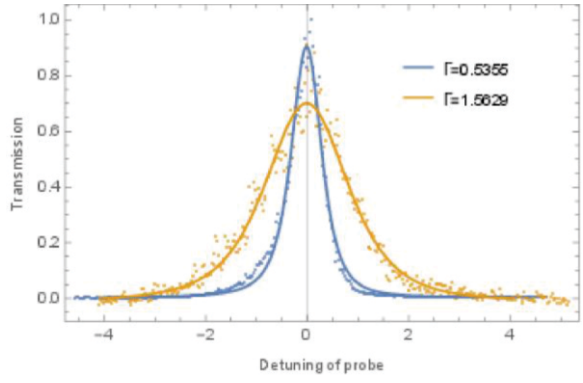


Figure 3

But the task of establishing true gain in this system by explicitmeasurements of input and output optical fields becomes non-trivial because the input optical probe field cannot be discriminated from the much stronger input optical coupling field either spatially or by measuring polarization features. The output probe field

also carries with it the local oscillator field strength. The group is now calibrating the system carefully in order to establish the true gain.

Narayanan's research during 2015-16 also included finding **non-Markovian signatures in atom-light interaction and their relevance to light absorption in photosynthesis**. Her collaborator in this work is **Atul V. (PhD student, RRI)**. Recently [A. Shabani, et. Al, Phys. Rev. E, **86**, 011915 (2012)], electron transport in photosynthetic light harvesting complexes have been mapped to atom-quantum-optical systems. Specifically, adjacent chromophores one of which gets excited by an incoming photon, along with its non-excited neighbour, are said to map to a V-level atomic configuration. Coherences in excitonic (bound electron and electron-hole) transport, which have been experimentally reported, can be explained with such a mapping.

Narayanan plans to initiate a thorough theoretical analysis of a non-Markovian interaction (interaction in which environmental correlations persist at a longer time scale over systemic time scales) of a proto-typical atomic V system with a thermal and vacuum EM field bath by employing numerical density-matrix analysis tools. She then aims to find its relevance in relation to the aforementioned excitonic transport phenomenon in photosynthetic light harvesting complexes.

Reji Philip's current research interests are nonlinear optics, laser produced plasmas and ultrafast phenomena.

His research efforts during 2015-16 in the area of nonlinear optics lay primarily in pursuance of the following problems -

(i) **Optical nonlinearity in nanostructured and other materials –** Collaborating with Tae Joo Park (Hanyang University, Republic of Korea), Mark G. Humphrey (Australian National University, Australia) and Ramakrishna Podila (Clemson University, USA), Philip has investigated the nonlinear optical behavior of nine-atom silver quantum clusters (QCs), graphitic carbon nitride (GCN), reduced graphene oxide (rGO) nanosheets, Ag2S-CuS nanocomposites, CdO nanomorphotypes, and a few other systems. The studies were mostly focused on graphene based materials.

The relatively large nonlinear absorption of Ag9 QCs compared to Ag nanoparticles (NPs) is revealed from open aperture Z-scan measurements carried out using 532 nm, 5 ns laser pulses. The superior limiting efficiency of Ag9 QCs is complemented by excellent chemical stability, which makes silver quantum clusters ideal candidates for optical limiting applications. The two-dimensional sheet-like structure of GCN is excellent for grafting metals and semiconductors, and even though the nonlinearity of pristine GCN is low the work has shown that its NLO properties can be enhanced substantially by grafting lightly with Ag9 QCs.

(ii) In yet another NLO study, Philip and his collaborators have reported the **wavelength dispersion of broadband, ultrafast optical limiting in reduced graphene oxide (rGO)**, measured by a single open aperture Z-scan using a white light continuum (WLC) source. This measurement also provided the two-photon absorption spectrum of rGO in the spectral range of 400-700 nm. The nonlinearity is shown to be arising from non-degenerate two-photon absorption, owing mostly to the crystallinity and extended π conjugation of rGO. The group has emphasized upon the ease of performing a WLC Z-scan when the nonlinearity is to be measured over broad wavelength ranges, and that it obviates the need for an ultrafast tunable laser, making it cost-economic compared to conventional techniques. The significance of the study lies in the fact that a wavelength dispersion study of optical power limiting is an important factor to be considered while designing potential optical limiters for laser safety applications.

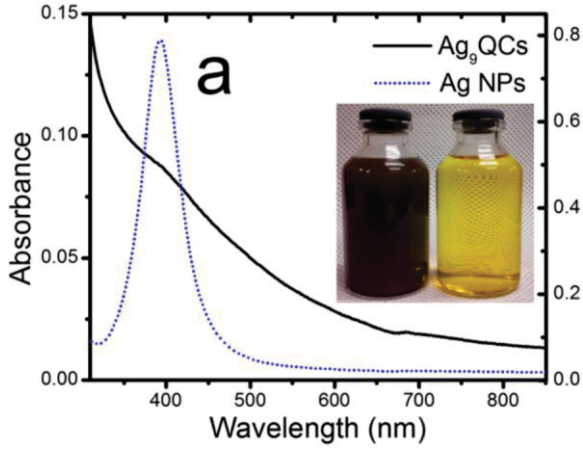


Figure 1: (a) UV−vis absorption spectra of nine atom silver quantum clusters and Ag nanoparticles. Inset shows photographs of Ag9 QCs (dark solution) and Ag NPs (bright yellow solution). Surface plasmon resonance is prominent in the absorption spectrum of Ag NPs [Image courtesy - Nonlinear Optical Investigations in Nine-Atom Silver Quantum Clusters and Graphitic Carbon Nitride Nanosheets, Kishore Sridharan, P. Sreekanth, Tae Joo Park, and Reji Philip, **J.Phys.Chem.C 119** (2015) 16314].

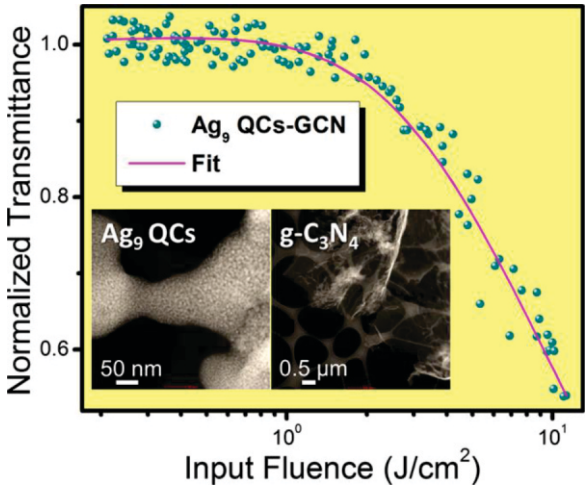


Figure 2: Normalized transmittance plotted against input laser fluence for nine-atom silver quantum clusters grafted on graphitic carbon nitride, for excitation at 532 nm using 5 ns laser pulses. The laser pulse energy used is 50 µJ. Solid curve is the numerical fit to theory. TEM images are shown in the inset [Image courtesy - Nonlinear Optical Investigations in Nine-Atom Silver Quantum Clusters and Graphitic Carbon Nitride Nanosheets Kishore Sridharan, P. Sreekanth, Tae Joo Park, and Reji Philip, **J.Phys.Chem.C 119** (2015) 16314].

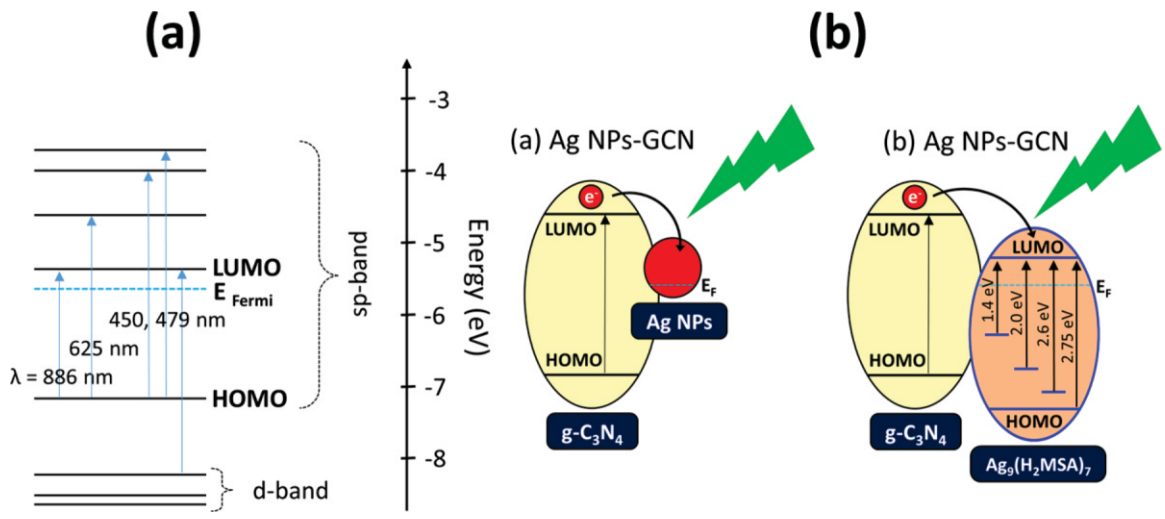


Figure 3: (a) Energy level diagram for the Ag9 cluster. (b) The composites form donor − acceptor complexes upon excitation by the laser beam, facilitating electron transfer [Image courtesy - Nonlinear Optical Investigations in Nine-Atom Silver Quantum Clusters and Graphitic Carbon Nitride Nanosheets, Kishore Sridharan, P. Sreekanth, Tae Joo Park, and Reji Philip, **J.Phys.Chem.C 119** (2015) 16314].

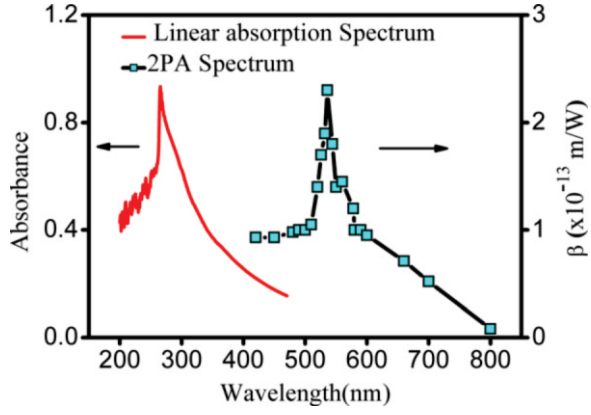


Figure 4: Wavelength dispersion of the two-photon absorption coefficient (β) in rGO. Linear absorption spectrum is also shown for comparison [Image courtesy - White light Z-scan measurements of ultrafast optical nonlinearity in reduced graphene oxide nanosheets in the 400–700 nm region, Sreekanth Perumbilavil, Pranitha Sankar, T. Priya Rose and Reji Philip, **Applied Physics Letters107** (2015) 051104].

(iii) Philip has also looked into the **impairment of electron mobility in doped-graphene due to increased electron-defect scattering**. In this collaborative work it was demonstrated through Raman spectroscopy, ultrafast spectroscopy, nonlinear transmission measurements and density functional theory that the graphitic dopant configuration is stable in graphene and does not significantly alter electron–electron or electron–phonon scattering (which is otherwise present in doped graphene) by preserving the crystal coherence length. [Dopant-configuration controlled carrier scattering in graphene, B. Anand, M. Karakaya, G. Prakash, S.S.S. Sai, R. Philip, P. Ayala, A. Srivastava, A.K. Sood, A.M. Rao and R. Podila, RSC Advances**5** (2015) 59556].

Within ultrafast phenomena, Philip's research in the last year consisted of the following:

(i) **Spectroscopic study of ultrafast laser-induced plasmas.** Philip has collaborated with Robert T. Sang (Griffith University, Australia) in this work. In continuation of previous year's work Philip and Sang carried out time-resolved

spectroscopic measurements of expanding plasma plumes generated by irradiating a solid zinc target with laser pulses of 7 ns and 100 fs durations in the ambient pressure range of 0.05–200 Torr of nitrogen. At the relatively high input fluence of 16 J/cm^2, fast and slow atomic species were found to appear at different times in the optical time of flight (OTOF) spectra, the dynamics of which was primarily determined by the pulse duration of the excitation laser. In fs LPP, the average speed of fast species was unaffected by an increase in ambient pressure, while in ns LPP, the speed was found to reduce with pressure. The slow species showed a sharp peak in the OTOF spectra with a narrow velocity distribution for fs LPP, indicating a large number density and low electron temperature, which was consistent with optical emission spectroscopic (OES) studies. On the other hand, for ns LPP, the OTOF of slow species showed a more broadened profile which could be attributed to strong plume–laser interaction. The dynamics of slow species was heavily influenced by the presence of shock waves, which led to the occurrence of much slower species at larger pressures. [Influence of pulse width on the laser ablation of zinc in nitrogen ambient, N. Smijesh, Kavya H. Rao and R. Philip, Appl. Phys. A**122** (2015) 460].

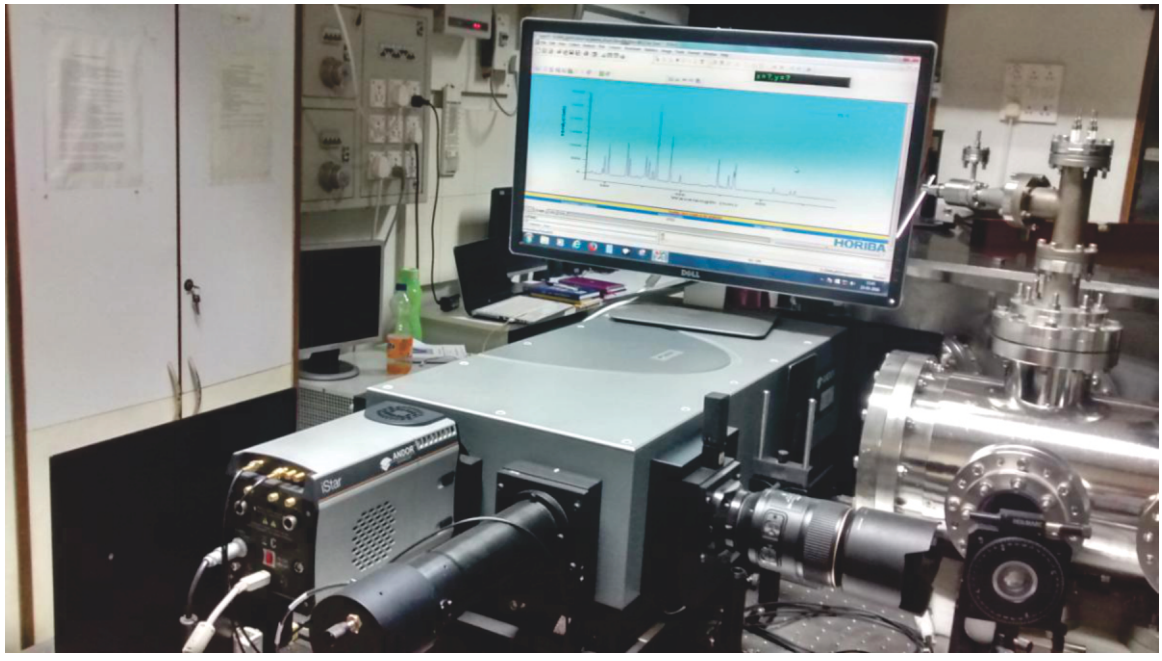


Figure 5: The newly acquired ICCD spectrometer from Andor Technology Ltd, UK, has augmented the laser plasma measurement capabilities of the lab. Expanding plasma plumes can now be imaged with a high temporal resolution of 2 x 10^{-9} seconds. Evolution of the emission spectra in time also can be recorded.

(ii) In another work in this area Philip has generated **highly ionized aluminum plasma by irradiating a solid Al target with 1064 nm, 7 ns pulses, for potentially extending the cut-off of higher-order harmonics.** For higher irradiation energies ionized species appear in the spectra at earlier times and a mix of ionized and neutral species appear at later times. At an optimized irradiation energy ~ 85 mJ, an isolated Al IV emission from the plasma plume is detected close to the target (0.5 mm) at earlier times (< 70 ns). The high ionization potential of Al IV species in such microplasmas would help drastically improve the cut-off of HHG typically to ~ 1.7 keV by irradiating the plasma at these earlier time scales with 800 nm, ~ 30 fs pulses having irradiation intensity > 6 × 10^{15} W/cm^2, once quasi-phase matching conditions are satisfied. [N. Smijesh, Kavya H. Rao, N. Klemke, R. Philip, I. Litvinyuk and R. T. Sang, Appl. Phys. Lett. (Communicated).]

Hema Ramachandran's areas of professional research interests lie in light in random media, few-atom and few-photon systems, and brain-computer interfaces.

Within light in random media, Ramachandran's research during this period focussed on **real-time imaging through fog.** Ramachandran has collaborated with Swapnesh Panigrahi, Julien Fade and Mehdi Alouini (all at University of Rennes, France) in this project.

Over the past few years, the group has achieved real-time imaging through random media by illuminating the scene with intensity modulated light followed by a quadrature lock-in discrimination scheme to extract the ballistic light (Light that passes unscattered through the intervening random medium, consequently in a straight line) with significant speedup achieved by efficient data processing and parallelisation on a graphics processing unit (GPU). Keeping in mind the potential applications of the above scheme, the group, in the past year, has tried to narrow down the frequency of the intensity modulated light by efficiently estimating the scattering properties of a turbid medium and to maximize ballistic photon discrimination by the lock-in scheme. Using the diffusion model for modulated photon transport and considering a noisy quadrature demodulation, the minimum-variance bounds on estimation of parameters representing the turbid medium were analytically derived and analysed. The existence of a variance-minimizing optimal modulation frequency was shown and its evolution with the properties of the intervening medium derived. Furthermore, a metric was defined to quantify the efficiency of ballistic photon filtering when imaging through turbid media. The analytical derivation of this metric showed that the minimum modulation frequency required for attainment of significant ballistic discriminations, sole dependence is on the reduced scattering coefficient of the medium for a high-scatter medium. They also found the dependence to be linear. [Real-time imaging through strongly scattering media: seeing through turbid media, instantly, Sriram Sudarsanam, James Mathew, Swapnesh Panigrahi, Julien Fade, Mehdi Alouini and Hema Ramachandran, submitted].

Ramachandran's foray into few-atom and few-photon systems consisted of:

(i) **Creation of novel structures using light**: Ramachandran's collaborators in this work were Vanessa Rodrigues (Manipal University), John Thomas (Manipal University), Santhosh Chidangil (Manipal University), and D. Mathur (TIFR). The group has demonstrated a novel and simple single-step method of inscribing optical elements on metal-coated transparent substrates. The technique, which they have an acronym for - LISA (Laser Induced Solid Ablation), demands very low laser energies (few nJ), which is easily sourced from a femtosecond laser oscillator, and is made possible by localised heating achieved on the metal. As a test for its accuracy, LISA was used to write Fresnel zone plates on indium and tungsten coated glass, with the number going up to 100 zones. Remarkable agreement was obtained between expected and measured values of the focal length achieved using LISA-made plates. The simplicity with which a high degree of automation can readily be achieved using LISA makes this a cost-effective method amenable to a wide variety of applications related to microfabrication of optical elements. [Microfabrication of Fresnel zone plates by laser induced solid ablation, Vanessa R M Rodrigues, John Thomas, Chidangil Santhosh, Hema Ramachandran, and Deepak Mathur, Accepted for publication in Journal of Optics].

(ii) **Time-delayed intensity-interferometry of emission from laser-cooled atoms**: [**Time-delayed intensity–interferometry of the emission from ultracold atoms in a steady-state magneto-optical trap, K Muhammed Shafi, Deepak Pandey, Buti Suryabrahmam, B S Girish and Hema Ramachandran, J. Phys. B: At. Mol. Opt. Phys. 49, 025301 (2016)].** In continuation of their working on time-delayed intensity-interferometry (TDII) of the emission from laser-cooled atoms, Ramachandran and her collaborators **Muhammad Shafi (PhD student, RRI)**, and **B.S. Girish (RRI)** have showed that not only is the measurement of second-order correlation a powerful technique that can reveal hidden periodicities such as coherent Rabi oscillations, it can also reveal information about the mean velocity of the thermal ensemble of emitters. The latter is possible even though the Doppler broadening of emission due to the motion of atoms is smaller than the natural line-width and is not directly measureable under these

experimental conditions. However, the elastically scattered light would have a Doppler profile determined by the velocity distribution of atoms, and hence the long-delay decay of TDII can provide the temperature of the emitting ensemble, as illustrated below:

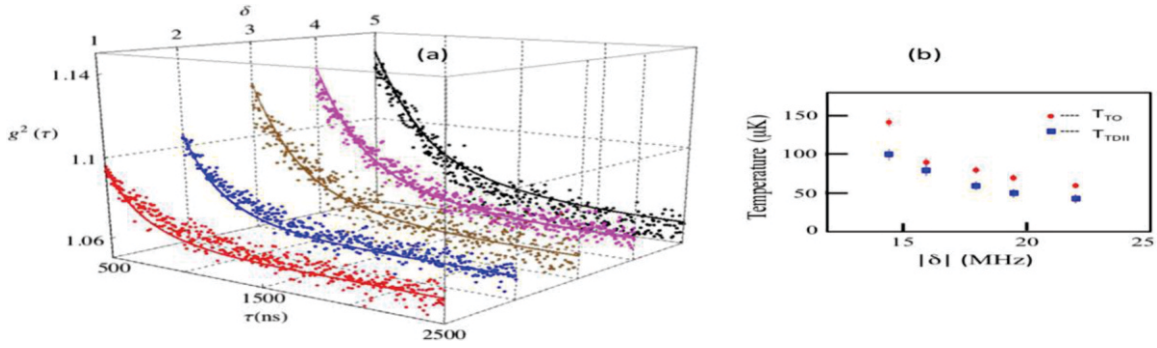


Figure (a) g(2) (τ) vs τ for various detunings, δ (1=-14.5MHz, 2=-16.1MHz, 3=-18MHz, 4=-19.4MHz, 5=-22MHz) of the cooling beam from the cooling transition. (b) The values obtained from TD II measurements are shown as dots. [Courtesy: Time-delayed intensity–interferometry of the emission from ultracold atoms in a steady-state magneto-optical trap, K Muhammed Shafi, Deepak Pandey, Buti Suryabrahmam, B S Girish and Hema Ramachandran, J. Phys. B: At. Mol. Opt. Phys. 49, 025301 (2016)].

Ramachandran's application-oriented research on Brain Computer Interface has made major progress in the period 2015-16. The Steady-State Visually Evoked Potential (SSVEP) (BCI systems that use the steady-state visually evoked potential (SSVEP) – a potential in the occipital area of the brain, evoked by an external visual stimulus oscillating at a steady frequency in the range 10 to 20 Hz - are the most studied especially because SSVEP is the easiest to record and measure. Typically these BCIs have several LEDs blinking at different frequencies, and by assigning each LED a certain task, the subject can be aided in initiating the corresponding task by directing his/her attention towards one of the LEDs and measuring the associated SSVEP) based Brain-Computer Interface (BCI) system developed in-house by Ramachandran and her collaborators, **Ramesh Balasubramanyam, S. Sujatha, K.B. Raghavendra Rao, S. Somasekar (all at RRI)** and RRI VSP students, has been optimised, and made robust. It is now extensively tested and validated, and has been shown to perform with >90% efficiency on over 10 volunteers. The systems work well both in a protected environment, as well as outdoors. The design has also been made compact and lightweight, and is battery-operable and thus portable. The group now proposes to test the system on motor-limited persons, who are the intended users of BCI systems.

Sadiq Rangwala's current professional research interests focus on molecule-light and molecule-molecule interactions, atom-cavity physics and ultra-cold ion atom collisions.

In the past year his research activities centred upon two major projects as described below –

(i) **Optical-bistability-enabled control of resonant light transmission for an atom-cavity system- [Rahul Sawant and S. A. Rangwala, Phys. Rev. A93, 023806 (2016)-Published 3 February 2016].** In this paper Rangwala and **Rahul Sawant (PhD student, RRI)** investigate numerically and theoretically the control of light transmission through a standing-wave Fabry-Pérot cavity containing atoms under a condition when the cavity mode beam and an intersecting control beam are both close to specific atomic resonances. A four-level atomic system is considered and its interaction with the cavity mode is studied by solving for the cavity field and atomic state populations. The theoretical conditions for optical bistability of the atom-cavity system are then calculated using the four-level system. The response of the intracavity intensity to an intersecting beam on atomic resonance is understood in the presence of both stationary atoms (closed system) and nonstatic atoms (open system) in the cavity. The nonstatic system of atoms is modelled by allowing for variable atomic state populations so as to incorporate the exchange of atoms in the

cavity mode, a model that corresponds to a thermal environment where atoms are moving in and out of the cavity mode volume. The control behavior with three- and two-level atomic systems has also been studied; so also the rich physics arising out of these systems for both closed and open atomic systems. The solutions to these three- and two-level models are used to interpret the steady-state and transient behavior observed by Sharma *et al.* [Phys. Rev. A91, 043824 (2015)].

(ii) **Optical control of resonant light transmission for an atom-cavity system [Arijit Sharma, Tridib Ray, Rahul V. Sawant, G. Sheikholeslami, S. A. Rangwala, and D. Budker, Phys. Rev. A91, 043824 (2015) - Published 15 April 2015]**. In this paper Rangwala, with **Arijit Sharma, Tridib Ray, Rahul V. Sawant (all PhD students, RRI)** and collaborators, have demonstrated the manipulation of transmitted light through an optical Fabry-Pérot cavity, built around a spectroscopy cell containing enriched rubidium vapor. Light resonant with the Rb87D2 (F=2,F=1)↔F' manifold is controlled by the transverse intersection of the cavity mode by another resonant light beam. The cavity transmission can be suppressed or enhanced depending on the coupling of atomic states due to the intersecting beams. The extreme manifestation of the cavity-mode control is the precipitous destruction (negative logic switching) or buildup (positive logic switching) of the transmitted light intensity on intersection of the transverse control beam with the cavity mode. The authors have experimentally investigated both the steady-state and transient responses.

Rangwala is also engaged in studying

(i) **Photodissociation of trapped Rb_2^+ in an ion-atom hybrid trap,** with **S. Jyothi and Tridib Ray [both PhD students, RRI], Sourav Dutta (DST-Inspire fellow, RRI),** A.R. Allouche (University of Lyon, France), Romain Vexiau and Olivier Dulieu (LAC, Orsay, France). In continuation of their work on this topic from last year the group has observed direct photodissociation of trapped Rb_2^+ molecular ions in the presence of cooling light for the Rb magneto-optical trap (MOT). Vibrationally excited Rb_2^+ ions were created by two photon ionization of Rb_2molecules formed photo-associatively in the Rb MOT and was trapped in a modified spherical Paul trap co-centric with the MOT. It was found that Rb_2^+ions could be trapped in the ion trap for >10 seconds in absence of the Rb MOT. However, the lifetime of Rb_2^+ ions was less than 500 ms in presence of the Rb MOT. Further investigations revealed that the lifetime did not depend significantly on the presence of ultracold Rb atoms but depended heavily on the presence of the Rb cooling laser beam. This has been attributed to direct photodissociation of Rb_2^+ by a 780 nm photon that excites the Rb_2^+ ion to a dissociating electronic state. The observed decay rate of the trapped Rb_2^+ ion signal in the presence of the MOT cooling light was in agreement with the calculated rates for Rb_2^+ photodissociation. The photodissociation mechanism due to the MOT light is expected to be active and therefore universal to all homonuclear diatomic alkali-metal molecular ions. The results have been submitted to Physical Review Letters and a preprint is available at arXiv: 1601.01119.

(ii) **Collisional cooling of light ions by co-trapped heavy atoms,** with **Sourav Dutta (DST-Inspire Fellow, RRI)** and **Rahul Sawant (PhD student, RRI)**: The most generic cooling and thermalization pathway at lowest attainable temperatures is via elastic collisions. In hybrid ion-atom traps, ions cooling to temperatures where low partial wave collisions dominate require the collisional cooling mechanism to be well understood and controlled. A critical step towards that goal lies in resolving the significant uncertainty regarding cooling of light ions by heavier neutral atoms. In this work the collaboration experimentally demonstrated, for the first time, the cooling of light ions by co-trapped heavy atoms. Trapped $^{39}K^+$ ions are cooled by localized ultracold neutral ^{85}Rb atoms for an ion-atom mass ratio for which many theoretical models predict ion heating. The rate at which the energy of the ions changes is modelled to determine the cooling rate of the $^{39}K^+$ ions, due to the presence of the ^{85}Rb atoms, in a magneto-optical trap. These results support the possibility that cooling of ions by localized cold atoms may hold for any mass ratio. The importance of the result lies in

furthering knowledge on possible configurations for quantum collisions and in understanding ultracold chemistry in trapped ion atom mixtures.

Some of Rangwala's other projects include

(i) Emergent symmetry in an interacting-ion system mediated by ion-atom collisions in a cold dilute gas of atoms
(ii) Reaching the s wave limit in ion atom collisions
(iii) A Virial theorem analysis of multipole ion traps – all with Niranjan Myneni (PhD student, RRI)
(iv) Normal mode splitting for higher order cavity modes in a coupled atom-cavity system with Niranjan Myneni, Sourav Dutta and Tridib Ray
(v) Non-destructive detection of ions using atom-cavity collective strong coupling with Sourav Dutta and Tridib Ray [RRI] and
(vi) State selective collision rate measurement in ion-atom mixtures with Sourav Dutta and Rahul Sawant.

Urbasi Sinha's areas of current professional research involve quantum information, quantum computation and quantum communication using single photons and experiments on quantum foundations.

Her work in the area of quantum foundations and quantum information theory over the last year has focused on

(i) Achieving a more complete understanding of the **limitations of the application of the superposition principle in slit based interference experiments.** Sinha and her collaborators have shown that in a regular double slit interference experiment; the wave function at the screen with both slits open is not exactly equal to the sum of the wave functions with the slits individually open one at a time. The three scenarios represent three different boundary conditions and as such, the superposition principle should not be applicable. However, most well-known text books in quantum mechanics and classical optics implicitly and/or explicitly use this assumption that is only approximately true. The group have used the Feynman Path Integral formalism to quantify contributions from non-classical paths in quantum interference experiments that provide a measurable deviation from a naive application of the superposition principle. **Fig. 1** shows representative classical and non-classical paths. Although direct experimental demonstration for the existence of these non-classical paths is difficult to present, theoretically the contributions from these non-classical paths can quantified in terms of the normalized version of the Sorkin parameter. Their earlier research on this problem had provided the first theoretical bound on this parameter.

During the year Sinha, along with Aninda Sinha (IISc, Bangalore) and Aravind HV (Joint Int. PhD student, IISc), has been able to derive an analytical formula for the normalized Sorkin parameter which they call "kappa". This analytic closed form expression is not only important from a theorist's point of view but also gives a handle on the parameters which determine kappa experimentally. The formula now makes it easier to "design" experiments in which kappa can be big and hence more easily measurable. The formula is also an excellent match with simulations of Maxwell's equations using Finite Difference Time Domain (FDTD) simulations. While FDTD simulations published earlier for certain parameter regimes took terabytes of memory and days to compute on a supercomputing facility, Sinha et al.'s kappa can be computed within seconds using standard software like Mathematica on a laptop.

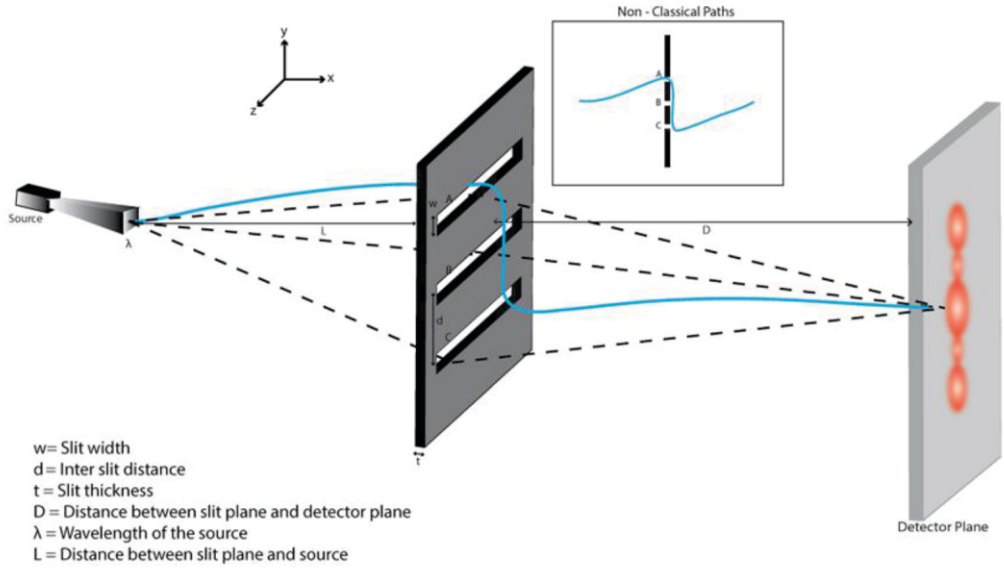


Figure 1: Observing Non classical paths in slit based interference experiments. The blue line is a representative non classical path; the dotted lines are representative classical paths. [Image courtesy: On the superposition principle in interference experiments, A.Sinha, A.H.Vijay and U.Sinha, Scientific Reports, 5 10304, 2015]

(ii) **Weak measurements -** In quantum theory, a physical observable is represented by a Hermitian operator as physically it can only have real eigenvalues. This stems from the fact that any measuring apparatus that is supposed to measure a physical observable will always yield a real number. However, reality of eigenvalue of some operator does not mean that it is necessarily Hermitian. There are examples of non-Hermitian operators which may admit real eigenvalues under some symmetry conditions. One may wonder if there is any way to measure a non-Hermitian operator, for example, the average of a non-Hermitian operator in a quantum state. In this work, Sinha and collaborators, Arun Pati [HRI, Allahabad] and Uttam Singh [PhD student, HRI, Allahabad] show that quantum theory allows inference of the expectation value of any non-Hermitian operator via weak interactions. The average of a non-Hermitian operator in a pure state is a complex multiple of the weak value of the positive semi-definite part of the non-Hermitian operator. They also prove a new uncertainty relation for any two non-Hermitian operators and illustrate it for the creation and annihilation operators, and the Kraus operators. [**Measuring Non-Hermitian operators via weak values**, A.Pati, U.Singh and U.Sinha, Physical Review A 92 052120, 2015]

Sinha's theoretical investigations include two more projects –

(iii) Diffraction based quantum interferometry in collaboration with **Simanraj Sadana (Phd student, RRI)** and Barry Sanders (University of Calgary, Canada) and

(iv) The manipulation of Entanglement Sudden Death in photonic systems in collaboration with **Ashutosh Singh (PhD student, RRI)** and Siva Pradyumna (former VSP student, RRI,now pursuing PhD in Italy).

Sinha's experiments that are congruent with her theoretical investigations have also made considerable progress during the last year. For the table-top version of her experiment on the detection of non-classical paths, Sinha is currently using a tunable Ti-Saphire laser system from Coherent Inc. in collaboration with Debadrita Ghosh (Project Assistant, RRI), **Surya Narayan Sahoo (PhD student, RRI)** and Nandini SG (VSP student, RRI). Experiments of this type in the infra-red domain fall in the realm of what are called precision experiments and are perhaps the hardest class of experiments to perform as the error control is of utmost importance to definitively ensure that the quantity being measured is indeed precise up to a certain order. **Fig. 2** shows the experimental set-up. A microwave version of the above experiment has also been set up at Gauribidanur field station and involves collaboration with the Radio Astronomy group at RRI, especially **R. Somashekhar** of the Electronics Engineering group (EEG). The setup uses

horn antennas, spectrum analyzers and home built slots and slot stands. The current version of the experiment **[Fig.3]** has been arrived at after several steps of noise and error analysis and is being conducted in collaboration with Rengaraj Aparijathan (former VSP student, RRI), **Surya Narayan Sahoo**, U Prathwiraj (Project Assistant, RRI) and **R. Somashekhar.**

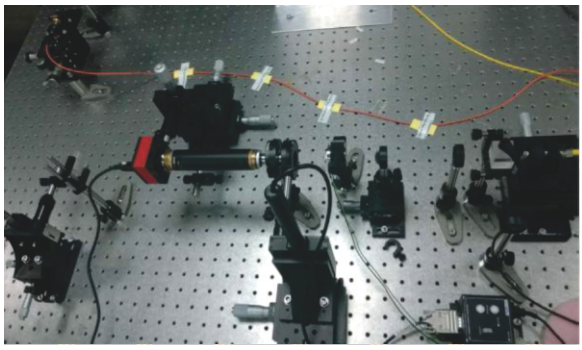


Fig. 2: Experiment to detect non-classical paths in quantum interference experiments.



Fig. 3: Microwave version of the experiment to detect non-classical paths.

In the research theme of weak interaction and weak measurements, **Sinha**'s experiment involves the use of a Mach Zehnder interferometer. **Fig. 4** below has a picture of the experimental set-up along with a measured interference pattern. Traditionally, weak measurements are done by weakly coupling the states of a quantum system to the pointer states and then obtaining a weak value by doing a strong measurement (post-selection). In this work, Sinha and **Surya Narayan Sahoo**, Gaurav Nirala (Project assistant, RRI) and Arun Pati present a different approach to infer the weak value of an operator via measuring visibility in a Mach-Zehnder interferometer. This method may be extended to measuring the weak values of a Non-Unitary operator which, in turn, can help in inferring expectation values for Non-Hermitian operators. This would be a novel result as usually one can measure only the expectation values of Hermitian operators in the lab; most known operators being Hermitian.

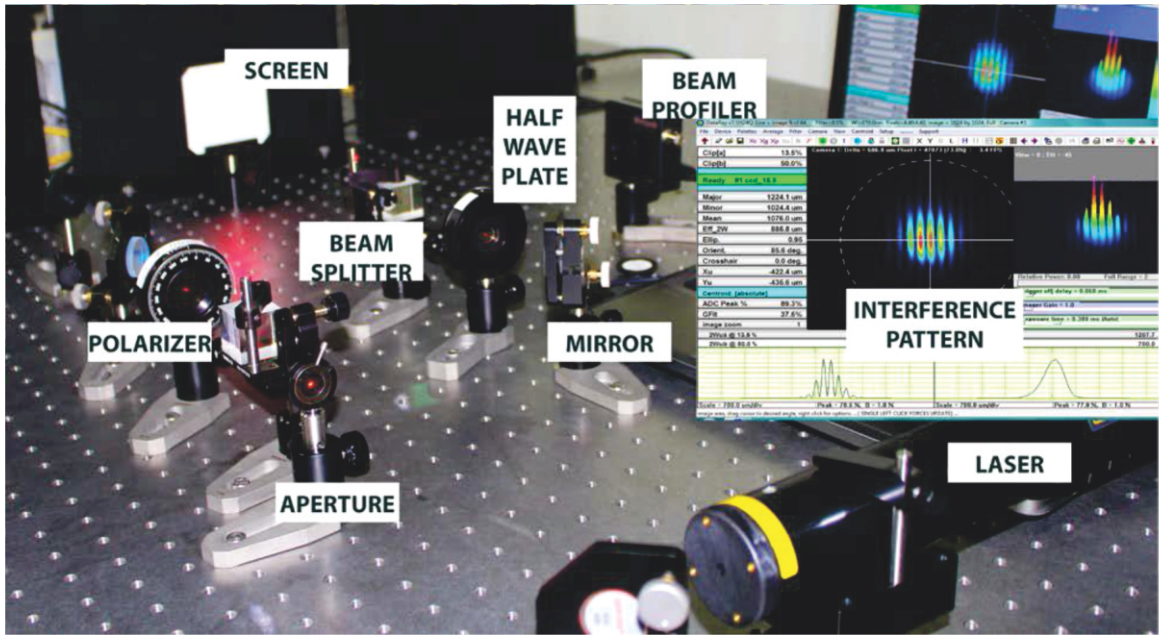


Fig. 4: Inferring expectation values of a Non Hermitian operator using a Mach Zehnder interferometer and weak measurements. The inset shows a typical interference pattern obtained in the interferometer.

While 2D quantum systems known as qubits are traditionally used for experiments in Quantum Computation, **Sinha**, **Surya Narayan Sahoo**, Debadrita Ghosh (project assistant in my lab), Piotr Kolenderski of the Nicolas Copernicus University in Poland and Thomas Jennewein of the Institute for Quantum Computing in Waterloo, Canada, are exploring higher dimensional quantum systems called qudits, especially the concept of maximally entangled qudits as subjects of interest for quantum information protocols and fundamental tests of quantum mechanics. Transverse spatial correlation obtained from spontaneous parametric down converted photons is one of the simplest methods that could be readily implemented using slit based interferometric systems.

Recently, it was shown that the angular spectrum of the incident pump can be transferred to the signal-idler bi-photon pair in SPDC process. Tapping onto this, the group has attempted to harness qutrit-qutrit correlations in spatial degrees of freedom by making the pump have a profile of a triple slit. They have studied how the idler profile is correlated with a given signal and established the qutrit-qutrit correlations for different experimentally viable parameters. This principle of generating spatially entangled photon qutrits could be easily extended to n–dimensional space and find wide applications, especially in Quantum Computing.

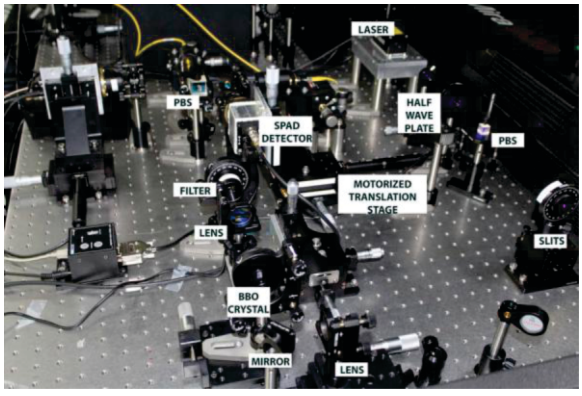


Fig 5: Measuring spatial correlations between qutrits in a Type II Spontaneous Parametric Down conversion source.

Sourav Dutta's research during 2015-16 lay in the areas of cooling and trapping of ultracold atoms, ions and molecules, photo-association of ultracold homonuclear and heteronuclear molecules, optical manipulation of atoms, ions and molecules, and cavity based detection of interactions. Some of the research projects that he undertook in the year are:

(i) **Vacuum Rabi Splitting (VRS) measurements in a dark MOT**: Collaborating with **Niranjan Myneni (PhD student, RRI)** and **S.A. Rangwala (RRI),** Dutta has implemented a dark spot ^{85}Rb MOT in which most (~ 99%) of the ^{85}Rb atoms are in the ground 5s (F = 2) state, as opposed to a bright MOT where a large fraction (~25%) of atoms is in the excited 5p state. When these ultracold atoms are placed within the mode volume of a Fabry-Perot cavity, collective strong coupling between atoms and cavity leads to vacuum-Rabi splitting (VRS). The implementation of the dark MOT has opened up the possibility to do continuous measurements of VRS using an on-axis weak probe beam. In all previous VRS measurements, the cooling/trapping lasers had to be switched off resulting in loss of atoms from the trap, and a new sample had to be loaded for each subsequent measurement. The dark MOT allows continuous and repeated VRS measurements on the same sample of trapped atoms making data taking significantly faster. The group has demonstrated a technique based on VRS (around the F = 2 → F' = 3 transition) to determine the number of atoms coupled to the cavity mode. This is especially important for a dark MOT since the MOT fluorescence (typically used in atom number determination) is too low for reliable measurements. This also allowed for a study on how VRS changes for higher order cavity modes (TEM10, TEM20 and TEM30 modes) and for inferring the density profile of the trapped atomic cloud.

(ii) **Optical bi-stability and all optical switching:** A closer look at VRS measurements done with different probe light intensities showed that VRS decreases with increasing probe intensity. The measurements also revealed an asymmetry in the line shape of the vacuum-Rabi peaks – a possible signature of optical bistability (OB). When the probe laser is locked to the F = 2 → F' = 3 transition and its power is scanned, the cavity transmission showed multi-stable behavior and a well developed hysteresis was seen in the input-output curve. The shape of the hysteresis could be controlled by another laser tuned near the F = 3 → F' = 3 transition. **Dutta**

and **Rangwala** also observed that the vacuum-Rabi peaks disappear when ~10 μW of light (slightly red detuned from the F = 3 → F' = 3 transition) is incident on the atoms from a transverse direction. The behaviour originates from atomic dynamics in the Λ-type energy level scheme formed by the F = 2 ↔ F' = 3 and F = 3 ↔ F' = 3 transitions. This phenomenon is used to demonstrate a fast all-optical switch that can be operated with micro-Watt powers.

(iii) **Non-destructive detection of ions by atom-cavity collective strong coupling:** As described above, implementation of the dark MOT allowed continuous measurement of VRS in a coupled atom-cavity system. **Dutta** and **Rangwala** took this system to a different level experimentally, by addition of trapped $^{85}Rb^{+}$ ions to the system. The trapped ions interact with the ultracold atoms in the dark MOT. The group then used the change in collective strong coupling of atoms to a mode of the optical cavity for measuring the interaction between ultracold ^{85}Rb MOT atoms and non-fluorescing $^{85}Rb^{+}$ ions. With the cavity tuned to the non-cycling $5s^2S_{1/2}$ (F = 2) → $5p^2P_{3/2}$ (F' = 3) transition frequency of atomic ^{85}Rb, they measure the vacuum Rabi splitting (VRS) in two cases: with ^{85}Rb atoms alone or with both $^{85}Rb^{+}$ ions and ^{85}Rb atoms overlapping the cavity mode. The VRS is different in the two cases and provides a rapid, non-destructive measurement of the ion-atom collisions. This is the first measurement of its kind. They also develop a rate equation model that describes the change in VRS originating from atom loss due to ion-atom interaction. Together the experiment and the model allow determination of the number of trapped $^{85}Rb^{+}$ ions. Extension of the above technique is expected to be useful in a variety of experiments including non-destructive detection of molecules and molecular ions, deterministic loading of ions into an ion trap and measurement of atom-field interactions.

(iv) **Two-photon photoassociation of LiRb:** Dutta had experimentally demonstrated two-photon PA of LiRb molecules at Purdue University. Working in collaboration with Jesús Pérez-Ríos, Yong P. Chen and Chris Greene from Purdue University, **Dutta** has observed interesting features in these two-photon PA spectra which they are trying to interpret. They are examining if this might allow production of ultracold LiRb molecules by stimulated Raman adiabatic passage (STIRAP).

M. Anil Kumar's areas of current professional research interests are Quantum Optics, Optomechanics and Foundation of Quantum Mechanics.

Over the year gone by **Kumar,** in collaboration with U. Satya Sainadh (Griffith University, Brisbane, Australia), has considered an optomechanical system and theoretically investigated how the presence of a small residual quadratic optomechanical coupling (QOC) along with a conventional linear optomechanical coupling (LOC) affects a multitude of other properties of the system such as mechanical quadrature squeezing, quantum non demolition (QND) measurements, entanglement between cavity and mechanical modes, normal mode splitting, optomechanical cooling and optomechanical sensitivity of the system to force, displacement, mass and inertia. [**Effects of linear and quadratic dispersive couplings on optical squeezing in an optomechanical system**, U. Satya Sainadh and M. Anil Kumar, Physical Review A 92,033824 (2015)]

Given the importance of mechanical quadrature squeezing in the field of gravitational wave detectors, it has become very important to answer how many these couplings - both LOC and QOC can affect it. The authors construct a Hamiltonian for the optomechanical system, where the optical field inside the cavity couples to the mechanical oscillator via both linear and quadratic displacements and there exists an optomechanical coupling LOC (g_1) and residual QOC (g_2) in the system. Using this Hamiltonian, they construct an equation of motion and then solve the equation of motion under steady state conditions to arrive at an expression for the mean number of photons (I) in the cavity. Also they construct equations of motion for small fluctuations, by which one can deduce stability of the system and as well as an expression for variance in position (Δx^2) and momentum (Δp^2) quadratures of the mechanical oscillator. If $\Delta x^2 = \Delta p^2 = 0.5$, then the system is said to be in the Standard Quantum Limit (SQL). When either of $\Delta x^2 < 0.5$ or $\Delta p^2 < 0.5$, SQL is said to be beaten and the corresponding quadrature squeezed.

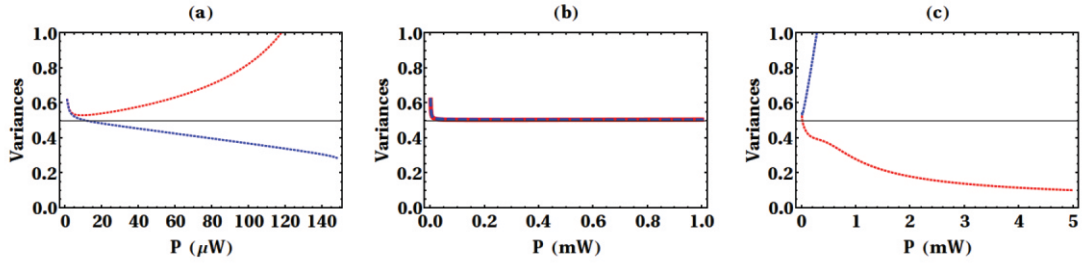


Fig 1. Variances in position (Δx^2) and momentum (Δp^2) plotted as function of Pump Power (P). The Black solid line at 0.5 depicts SQL. The system parameters are detuning$\Delta = \omega_m$, thermal bath temperature T=1 mk and QOC ($\frac{g_2}{g_1}$) values are (a)-10^{-2}, (b) 0 and (c)10^{-2}respectively with LOC fixed at $g_1 = 1351.38$ Hz.

In Fig.1 above the red and blue curves represent variance in position (Δx^2) and momentum (Δp^2) plotted as a function of input power (P), for various QOCs. The black solid line depicts SQL and the value of variance in a quadrature below this line represents squeezing of the corresponding quadrature. From Fig 1(b) it is evident that we find quadratures can at most reach SQL with LOC alone while squeezing is observed only in case of Fig 1(a) and (c). The squeezing can thus be thought of as arising with the inclusion of residual QOC in the system, which results in a change of mechanical oscillator frequency $\omega_m$to an effective $\omega_m$that affects the quadrature. In Fig 1(a) the QOC was chosen as negative, producing squeezed states in momentum quadrature. Whereas in Fig 1(c) the QOC was chosen positive and the modified mechanical oscillator frequency now results in position quadrature squeezing. The squeezing can be improved beyond 3 dB limit (> 50% below the SQL) at 1.3 mW, and further squeezing can be achieved by increasing the input power.

Sanjukta Roy's research efforts during the past year involved

(i) Quantum entanglement with ultracold Rydberg atoms and
(ii) Anderson localisation of quantum gases in disordered potentials.

(i) Quantum Entanglement is an important phenomenon in Quantum mechanics in which two or more particles are generated or interact in such a way that their quantum states are correlated and cannot be described independently even though the individual particles may be separated spatially. The correlations exhibited by entangled states have no classical analog. Quantum entanglement has important applications in emerging quantum technologies such as quantum information processing, quantum cryptography and teleportation.

Control and manipulation of ultra-cold Rydberg atoms offer a promising avenue for quantum information processing. Rydberg states are highly excited atomic states with a large principal quantum number n near the ionisation threshold. Atoms in Rydberg states exhibit interesting characteristic features such as large dipole moments. For example, Rydberg states with a principal quantum number n~50 have a dipole moment few thousand times that of water molecule. This makes the Rydberg atoms highly polarisable with static polarisability scaling as $n^7$and hence very sensitive to DC or AC electric fields. Such a large dipole moment gives rise to large interaction between Rydberg atoms via dipole-dipole coupling which scales as $1/R^3$where R is the inter-atomic distance. The interaction energy between two Rydberg atoms exhibit a strong dependence on the principal quantum number n and can be tuned from the Van der Waals regime to the $1/R^3$ regime by using an electric field or by varying the inter-atomic distance. Rydberg interactions between ultra-cold Rydberg atoms can enable the generation of entangled states and lead to quantum information processing via realisation of fast quantum gates.

The generation of quantum entanglement and the realisation of a Quantum gate with two single Rydberg atoms has been achieved elsewhere. However, for the purpose of scalability of quantum information processing, it is desirable to realise mesoscopic entanglement with a large number of atoms. The objective of

this experiment is the generation of mesoscopic entanglement using Rydberg blockade. The proposal is to create mesoscopic entanglement in an ensemble of ultra-cold atoms with a single control atom. The entanglement can be implemented in a single step with high fidelity within a time-scale of one micro-second by combining long-range Rydberg interactions with the quantum interference phenomena of Electromagnetically Induced Transparency (EIT). This would eliminate the need for individual addressing of the ensemble of atoms and hence would enable the realisation of a fast mesoscopic quantum gate. In this direction, a stable magneto-optical trap has been realised in the experiment which would act as a cold atom reservoir for the single-atom trap. The alignment of the laser beam for realisation of a microscopic dipole trap for single atom trapping is in progress. Roy's collaborators in this project were **Hema Ramachandran (RRI)**, Reshma Ravi (VSP student, RRI) and Manikandan Konappan (VSP student, RRI).

(ii) Study of 3D Anderson localisation with ultra-cold atoms in disordered potentials - **[Measurement of the mobility edge for 3D Anderson localization, G. Semeghini, M. Landini, P. Castilho, S. Roy, A. Trenkwalder, G. Spagnolli, M. Fattori, M. Inguscio and G. Modugno, Nature Physics 11, 554 (2015). (Highlighted in Nature Physics: News and Views)]**

Roy has collaborated with G. Semeghini (LENS and Dipartimento di Fisica e Astronomia, Universite di Firenze, and CNR-INO, Sesto Fiorentino, Italy), M. Landini (LENS and Dipartimento di Fisica e Astronomia, Universite di Firenze and CNR-INO, Sesto Fiorentino, Italy), P. Castilho (LENS and Dipartimento di Fisica e Astronomia, Universite di Firenze, Sesto Fiorentino, Italy), A. Trenkwalder (LENS and Dipartimento di Fisica e Astronomia, Universite di Firenze and CNR-INO, Sesto Fiorentino, Italy) , G. Spagnolli (LENS and Dipartimento di Fisica e Astronomia, Universite di Firenze and CNR-INO, Sesto Fiorentino, Italy), M. Fattori ((LENS and Dipartimento di Fisica e Astronomia, Universite di Firenze and CNR-INO, Sesto Fiorentino, Italy), M. Inguscio ((LENS and Dipartimento di Fisica e Astronomia, Universite di Firenze and INRIM, Torino, Italy) and G. Modugno (LENS and Dipartimento di Fisica e Astronomia, Universite di Firenze and CNR-INO, Sesto Fiorentino, Italy) in this project.

SOFT CONDENSED MATTER

Overview:

In recent years, soft condensed matter physics or "soft" physics has emerged as a field of research in its own right within the broader field of condensed matter physics. Soft materials, constituted by macromolecules that are held together by weak inter-macromolecular forces, are characterized by complex structures and phase behaviours. Colloidal suspensions and emulsions such as milk and paint, polymeric and biological materials, foam and liquid crystals are some common examples. The sizes of the macromolecules that constitute these materials are typically between a few nanometers and a few micrometers. In contrast to atomic systems whose relaxation times are of the order of picoseconds, soft materials relax on time scales that usually lie between 10^{-8} and 10^{3} seconds, which gives rise to long-lived metastable states. The structure and dynamics of these materials can therefore be easily studied using relatively simple laboratory techniques. Usually characterized by elastic constants that are many decades lower than those of traditional atomic solids, soft materials are viscoelastic and easily deformable and can be used in the study of a variety of non-equilibrium phenomena. Their properties are determined not only by their response to external forces but also by thermal fluctuations. The ease with which inter-constituent interactions can be modified in soft materials ensures that newer materials with interesting and useful properties can also be engineered from them. Their structural complexity, symmetries and mechanical flexibility make soft materials ideal model systems for applications as well as tests of ideas from statistical physics and condensed matter theory.

The soft condensed matter group at RRI is engaged in research on colloids, polymers, nano-composites, amphiphilic systems, synthesis, characterization and physical studies of liquid crystals and other exciting new areas such as biological physics.

Current research interests:

Liquid Crystals, Nano-composites and Polyelectrolytes

Experimental and theoretical studies have been undertaken at RRI to deal with the structure- property relations of 'soft' materials, which are easily deformable by external stresses, thermal fluctuations, electric, and magnetic fields. Among these soft materials, thermotropic liquid crystals consisting of highly anistropic organic molecules, banana mesogens with spontaneous breaking of macroscopic chirality, nano-composite materials, liquid crystals formed of bent-core hockey stick shaped molecules, polymers and biomaterials such as biomolecules and cells are being studied using a variety of experimental techniques. The interplay between the different degrees of freedom and various constraints present in these systems often give rise to rich and complex behaviour that can be exploited for potential technological applications. Examples of such work are the recent studies of pseudo-polar tilted smectic phases exhibited by bent core hockey stick shaped molecules, monolayer to interdigitated partial bilayer Smectic C transition in thiophene-based spacer mesogens and synthesis and characterisation of novel isoxazole-based banana liquid crystals from naturally occurring curcumin – a plant with medicinal properties and thus of considerable biological importance.

The chemistry wing of the Soft Condensed Matter Group is involved in the design, synthesis and characterisation of novel liquid crystalline materials that exhibit remarkable electronic and optoelectronic properties. This group has synthesized a number of monomeric, oligomeric, polymeric and ionic liquid crystalline materials. The synthesis of liquid crystalline materials using microwave heating has also been carried out with a view to find quick and environment-friendly synthetic routes. During the period 2015-2016, certain iodine-free discotic electrolytes were synthesized, characterized and applied in dye-sensitized solar cells. Various other materials, which were synthesized and investigated primarily for their applications in solar cells, were self-assembling, disc shaped LC material for bulk hetero-junction or BHJ solar cells. Liquid crystals derived from new U-shaped azobenzene liquid crystals were synthesized and characterized for their photoswitching properties. Apart from these, the group has also tailored the cholesteric plane spacing, dielectric relaxation and optical properties of high temperature chiral nematic phase LCs by UV Irradiation.

The incorporation of nanomaterials such as metal-nanoparticles like gold, silver or copper, quantum dots of materials such as thiolated graphene oxide, luminescent CdTe or CdSe and carbon nanotubes, in the supramolecular order of liquid crystals is likely to lead to novel materials for many applications. With this view, a research program has been initiated to prepare and functionalise these nanomaterials with discotic as well as nematic molecules and disperse them in monomeric, oligomeric and polymeric discotic liquid crystals with properties such as ferroelectricity. The dispersion of such functionalised nanomaterials in columnar matrix has been found, especially, to enhance physical properties such as their thermodynamic properties, elastic constants, dielectric, conductivity and photoconductivity, significantly leading to applications in fields such as photovoltaics.

One of the present research interests of the SCM group is in investigating electric-field induced chiral symmetry breaking in bent-core liquid crystals (BCLC) made of achiral molecules. The structure and properties of novel field-induced dark mesophases such as the lamellar dark conglomerate (DC) phase composed of electro-optically switchable macroscopic chiral domains are being studied, using a variety of techniques like optical microscopy, dielectric spectroscopy and X-ray diffraction. Field dependent shape transitions, exhibited by the nucleating chiral domains, which form these mesophases, are also being studied in order to understand the observed enantio-selectivity. During the period 2015-16, the group has been studying the synchronization of conformational chirality in liquid crystals made up of achiral molecules. Using two known BCLCs – NNMTB and PDMBC in various concentrations – the group has shown the existence of three types of lamellar mesophases: a dark enantiomeric (DE) phase with a single homochiral domain, dark conglomerate (DC) phase characterized by macroscopic homochiral domains of opposite handedness, and thirdly a birefringent lamellar

SmCP with flat layers with the minimum conformational neighbor-to-neighbor packing of molecules resulting in unencumbered molecular rotations. Dielectric parameter of the 3 mesophases turns out to be the maximum for the SmCP phase as expected, with progressive reduction in the mixtures, DE and DC, as the conformer packing efficiency increases and the layer deformation becomes more severe. The progressive evolution of homochirality as a function of the relative concentration of the achiral constituents as observed in this system clearly shows the role of an intrinsic coupling of molecular conformational chirality. This technique can also provide a control for tuning macroscopic chirality and for optimizing chiroptical properties for applications.

Another area of interest is in understanding the unusual occurrence of a reentrant lamellar phase in bent-core liquid crystals. Phase reentrance is a state where a less ordered phase characteristic of a higher temperature reappears again below a more ordered one at a lower temperature. This is extremely rare in the case of BCLCs and very few examples are known to exist. The group has synthesized a novel achiral BCLC compound that apparently shows reentrance characteristics as evidenced by their initial electro-optic and dielectric studies.

Phase Behaviour of Ionic Surfactants

The effect of adsorbing counterions and polyelectrolytes on the phase behavior of ionic surfactants is being investigated using a variety of experimental techniques. The main objective of these studies is to find conditions under which novel aggregate morphologies and phases can be stabilized in these systems. Theoretical modelling of these systems is also planned. The effect of salt on the adsorption of polyelectrolytes on oppositely charged surfactant bilayers has been explored already. The thickness of the polyelectrolyte layer appears to depend on the salt concentration, the reason for which is currently under investigation. Recent experiments on the adsorption process, instead of looking at a single charged surface as in earlier experiments, are using a novel setup of periodic stack of charged surfactant bilayers that can be probed by X-ray scattering techniques.

Structure of DNA-Surfactant Complexes

Structure of DNA-cationic surfactant complexes is being investigated using x-ray diffraction. The main focus of the study is to stabilize different structures of these complexes by changing parameters such as the size of the surfactant molecule and the nature of its counterion.

Organization of Sterols in Membranes

The phase behaviour of lipid membranes containing different sterol molecules is being studied, with a view to understanding the organization of these biologically important molecules in the membrane. Further experiments are underway to probe the orientation of these molecules in the membrane.

Organization of Mononucleotides on Lipid Membranes

The group has studied the organization of mononucleotides on lipid membranes to show that these molecules form dense patches on the membrane surface, which is an interesting result since such an arrangement is a prerequisite for their polymerization into long chains. The experiment could have relevance in understanding the physics behind the formation of self-replicating long-chain RNA-like polymers in the cellular environment.

Colloids and Complex Fluids

Experimental investigations of the structure, dynamics and rheology of non-Newtonian fluids and aging suspensions, soft glassy rheology, flow-structure correlations in complex fluids, rheological chaos and the nonlinear dynamics of shear flows, interfacial instabilities, the design of viscometers to measure complex flows, the stability of colloidal suspensions, the sedimentation of colloidal gels, micellar packings, controlled, targeted drug delivery using copolymer micelles as vehicles for drug delivery, the physics of granular media are being carried out.

Experimental tools such as static and dynamic light scattering, rheology, cryogenic scanning electron microscopy, ultrasound attenuation spectroscopy and high-speed imaging are being used extensively for these studies. Many of these investigations involve

collaborations with engineers and theoretical physicists working in the areas of statistical mechanics and materials science.

Some specific experiments that were performed in the last year include falling ball experiments on aging Laponite (synthetic clay) colloidal suspensions, kinetics of the glass transition of fragile soft colloidal suspensions of Laponite and dynamical heterogeneities in such suspensions when pushed to a glassy state. Further explorations into the properties of Laponite have shown a glassy transition in fragile soft colloidal suspensions of the material in the presence of probe particles. The experiment has studied microscopic relaxation processes of aging Laponite suspension (a model glass former) with embedded polystyrene beads used as probe particles, via dynamic light scattering (DLS) techniques. It is observed that the fragility parameter, D, that quantifies the rapidity of approach towards eventual kinetic arrest, increases with the concentration of polystyrene particles but decreases as the size of the particles increases. Apart from Laponite, natural clay and colloidal gels formed of aqueous solutions of Na-montmorillonite nanoclay particles are also under investigation with special emphasis on studies of the exfoliation and stability of natural clay in aqueous suspensions, effect of electrolyte on the microstructure and yielding of colloidal clay and aggregation and stability of colloidal clay-water suspensions in the presence of salt. The latter two studies could throw light on certain geophysical phenomena such as quicksand, river delta formation and even on physical factors behind landslides etc.

Biophysics

The Biophysics group at RRI encompasses experimental, theoretical and computational studies of various biological systems.

A physicist's approach to biological systems provides a novel perspective on how living machinery inside a cellular factory works. The group at RRI aims at achieving a quantitative physical description of dynamical phenomena occurring in cells at various levels. They are interested in nanoscale molecular structures that dominate interactions in DNA, protein segregation and self-assembly, DNA-protein complexes such as chromatin fibres, and signaling at the level of the cell membrane, aided by active cellular dynamics. They also investigate dynamical phenomena in neuronal cells leading to shape transitions and active mechanical responses. To quantify these studies, novel state-of-the-art techniques are developed in-house: for example, single molecule resolution nano-devices that help in deciphering secrets of biological nano-world and ultra-sensitive force measurement methods to probe mechanical responses of single cells. A shear device developed and constructed in-house to study cell adhesion properties in conjunction with fluorescence microscopy is the latest addition to this list. The device can create well-defined cell geometries when used with micro-patterning techniques; more importantly, help quantify cell adhesion through measurements on cell detachment under shear.

A recent study on axonal shape instabilities by the Biophysics group at RRI has yielded an important result. Using genetic means to express fluorescent synaptic vesicles it has been shown that transport in axons is not affected by 'beading' suggesting that 'traffic jam' is not the cause behind 'beading' as previously hypothesized by other workers in the field.

Glass and quartz nanopores of sizes about 6-800 nm constructed by the group have been characterized to enable detection of individual DNA molecules translocating through these nanopores. Efforts are also being made to measure the elastic properties of biological cells by forcing them to traverse through micropores against a bias voltage, using resistive pulse techniques.

Apart from experiments, theoretical and computational approaches described in greater detail in the Theoretical Physics section of this report are also being employed at RRI to decode biological systems. These are aimed at not only deciphering quantitative experiments but also to predict novel mechanisms. This subject is a rapidly expanding area of research at RRI and overlaps with other traditional topics like non-equilibrium statistical mechanics, membrane- and polymer physics.

Theoretical Studies

Theoretical work in the SCM group primarily focuses on the theory of elasticity and topological defects in soft matter. Orientational (such as nematic, vector, and hexatic) tangent-plane order on two-dimensional membranes deformable in three dimensions suffers frustration on curved membranes. Recently, the group has put forth a theoretical model to explain the topological instability in lyotropic smectic-A liquid crystals under hydration conditions, especially the growth of tubule-like structures and beads.

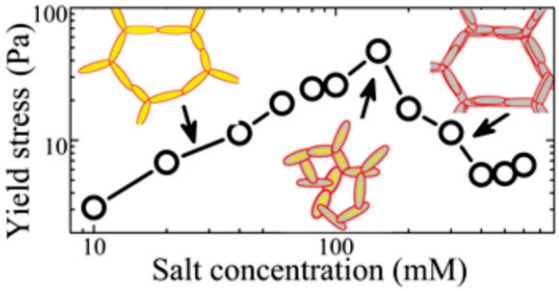
This group is also interested in solution- and melt-grown polymer crystallites such as polyethylene. Polyethylene for example, shows spherulitic structures made up of helicoidal lamellae that break chiral symmetry. A phenomenological theory for this has been given already. But apart from this morphology, polycrystallites also exhibit other diverse morphologies such as chair-, tent- and scroll structures. Attempts are being made to formulate a phenomenological theory based upon the interplay between elasticity and topological defects to explain the stability of observed morphologies.

Ranjini Bandyopadhyay's area of expertise, while largely in the field of rheology studies of soft condensed matter, is manifold. She is interested in structure, dynamics and rheology of non-Newtonian fluids; aging and soft glassy rheology, flow-structure correlations in complex fluids, micellar packings, controlled and targeted drug delivery using copolymer micelles as vehicles for drug delivery, interfacial instabilities, designing viscometers to measure complex flows, the stability and sedimentation of colloidal suspensions and the physics of granular media.

Her stability and sedimentation studies of colloidal suspensions have led Bandyopadhyay to explore clay tactoids or platelets using either artificial Laponite or Na-montmorillonite clay as her model systems. During the last year, she has pursued the following projects in this realm:

(i) **Evaluation of the exfoliation and stability of natural clay in aqueous dispersions** with **Samim Ali (PhD student, RRI)**. In aqueous dispersion, the powdered minerals of natural clay swell on absorption of water and exfoliate into smaller entities, known as tactoids, with electric double layers on their surfaces. The concentration dependence of, and time taken for, the exfoliation process play an important role in the dispersion behavior of tactoids [Langmuir, 2013, 29, 12663−12669]. Their newest article, [Samim Ali and Ranjini Bandyopadhyay, **Applied Clay Science 203, 85 (2015)**] focuses on the effects of screened Coulomb repulsions and the osmotic pressure of the Na+ counterions on the exfoliation of natural clay tactoids. Ultrasound attenuation spectroscopy was their chosen method to estimate the degree of exfoliation (the dispersibility) of tactoids at different clay concentrations, added salts and ages of the clay suspensions. They found that the dispersibility decreases with increasing clay concentration due to the combined effects of Coulomb repulsions and reverse osmotic pressure. However, at the jamming transition, the strong screened Coulomb repulsions become a dominant factor. Bandyopadhyay and Ali also measure the ultrasound induced colloidal vibration current to study the influence of clay dispersibility on the suspension stability behavior of the arrested phases formed at different ionic conditions.

(ii) **Effect of electrolyte on the microstructure and yielding of aqueous dispersions of colloidal clay** again with **Samim Ali [**Samim Ali and Ranjini Bandyopadhyay, **Soft Matter, 12, 414 (2016)].** Na-montmorillonite is a natural clay mineral and is available in abundance in nature. The aqueous dispersions of charged and anisotropic platelets of this mineral exhibit several non-ergodic kinetically arrested states ranging from soft glassy phases dominated by interparticle repulsions to colloidal gels stabilized by salt induced attractive interactions. When the salt concentration in the dispersing medium is varied systematically, viscoelasticity and yield stress of the dispersion shows non-monotonic behavior at a critical salt concentration, thus signifying a morphological change in the dispersion microstructures. The group directly visualizes the microscopic structures of these kinetically arrested phases using cryogenic scanning electron microscopy and observes the existence of honeycomb-like network morphologies for a wide range of salt concentrations. The transition of the gel morphology, dominated by overlapping coin (OC) and house of cards (HoC) associations of clay particles at low salt concentrations to a new network structure dominated by face-ã-face coagulation of platelets is observed across the critical salt concentration. Assessments of the stability of these gels under gravity using electroacoustics for concentrated clay dispersions for a wide concentration range of externally added salt as mentioned above is useful in our understanding of many geophysical phenomena that involve salt induced aggregation of natural clay minerals.



(iii) **Aggregation and stability of anisotropic charged clay colloids in aqueous medium in the presence of salt** with **Samim Ali [**Samim Ali and Ranjini Bandyopadhyay, **Faraday Discussions (2016) DOI: 10.1039/ C5FD00124B].** Na-montmorillonite nanoclay as described in project (ii) earlier is a colloid of layered mineral silicate. When dispersed in water, this mineral swells on absorption of water and exfoliates into platelets with electric double layers on their surfaces. Even at low particle concentration, the aqueous dispersion can exhibit a spontaneous ergodicity breaking phase transition from a free flowing liquid to nonequilibrium, kinetically arrested and disordered states such as gels and glasses. Bandyopadhay and Ali have shown that the stability of clay gels can be enhanced by adding salt to already prepared clay dispersion in deionized water, rather than by adding the clay mineral to a previously mixed salt solution [Applied Clay Science, 2015, 114, 85–92]. In their recent work, they directly track the collapsing interface of sedimenting clay gels using an optical method and show that adding salt after dispersing the clay mineral does indeed result in more stable gels even in very dilute dispersions. These weak gels are seen to exhibit transient collapse after a finite delay time, a phenomenon observed previously in depletion gels. The velocity of the collapse oscillates with age of the sample. However, the average velocity of collapse increases with sample age upto a peak value before decreasing at higher ages. With increasing salt concentration, the delay time for transient collapse decreases, while the peak value of the collapsing velocity increases. Using ultrasound attenuation spectroscopy, rheometry and cryogenic scanning electron microscopy, they have confirmed that morphological changes of the gel network assembly, facilitated by thermal fluctuations, lead to the observed collapse phenomenon. Since clay minerals are used extensively in polymer nanocomposites, as rheological modifiers, stabilizers and gas absorbents, the results reported in this work are extremely useful for several practical applications and also for understanding geophysical phenomena such as the formation and stability of quicksand and river deltas in the obvious presence of considerable natural salinity.

Under the broad theme of aging and soft, glassy rheology, Bandyopadhay has been engaged in answering the following questions over the year gone by:

(i) **Kinetics of the glass transition of fragile soft colloidal suspensions** with collaborators**, Debasish Saha, (PhD student, RRI)** and Yogesh M. Joshi (IIT Kanpur) [Debasish Saha, Yogesh Joshi and Ranjini Bandyopadhyay, **Journal of Chemical Physics, 143, 214901 (2015)**]. Microscopic relaxation timescales are estimated from the autocorrelation functions obtained by dynamic light scattering experiments for Laponite suspensions with different concentrations (C_L), added salt concentrations (C_S) and temperatures (T). It has been shown in an earlier work [Soft Matter 10, 3292 (2014)] that the evolutions of relaxation timescales of colloidal glasses can be compared with molecular glass formers by mapping the waiting time (t_w) of the former with the inverse of thermodynamic temperature (1/T) of the latter. In this work, the fragility parameter D, which signifies deviation from Arrhenius behavior, is obtained from the fits to the time evolutions of the structural relaxation timescales. For Laponite suspension, D is seen to be independent of C_L and C_S, but is weakly dependent on T. Interestingly the behavior of D is observed to corroborate the behavior of fragility in molecular glass formers with respect to equivalent variables. Furthermore, the stretching exponent (β) that indicates the width w of the spectrum of structural relaxation timescales is seen to depend on t_w. Similar to how the Kauzmann temperature is defined for molecular glasses, a hypothetical Kauzmann time scale (t_k) is defined at which w diverges. On the other hand, equivalent to how Vogel temperature is defined in molecular glasses, a hypothetical Vogel time scale t^{∞}_{α} is defined.

Interestingly a correlation is observed between t_k and t^{∞}_{α}, which is again remarkably similar to that known for fragile molecular glass formers. A coupling model along with t_w-dependence of the stretching exponent, β is used to analyze the correlation between t_k and t^{∞}_{α}. Overall; the work shows that Laponite colloidal suspensions exhibit several striking similarities with the behaviour of molecular glass formers.

(ii) **Fragile behavior of a soft glassy colloidal suspension in the presence of probe particles with Debasish Saha**, **Sanjay K. Behera (PhD student, RRI)**, and **Paramesh Gadige (Postdoctoral fellow, RRI)**.In this work, the microscopic relaxation processes of aging Laponite suspension (a model glass former) with embedded polystyrene beads, used as probe particles, are studied by dynamic light scattering (DLS) experiments. The polystyrene beads, being larger in size than the Laponite particles, behave as the less mobile regions in the suspension. Intensity autocorrelation functions measured in DLS experiments show the existence of two-step relaxation processes in these suspensions. The fast relaxation process is identified as due to the diffusion of a Laponite particle inside the cage formed by its neighbouring like particles, while the slow relaxation process is interpreted as the structural relaxation in the presence of externally added less mobile polystyrene beads. The fragility parameter D, which quantifies the rapidity of approach towards eventual kinetic arrest, is calculated from the evolution of the structural relaxation time for different concentrations and sizes of the polystyrene beads. D is seen to increase with the concentration of polystyrene particles, but decreases as the size of the particles increases. The observed results are compared with theoretical and simulation results on the random pinning in binary mixtures, where it is observed that the kinetic fragility parameter (KV_{FT}= 1/D) decreases with increasing pin concentration.

(iii) **Synthesis and study of the glass transition of highly polydisperse thermoresponsive poly (N-isopropylacrylamide) particles with Sanjay K. Behera**, **Debasish Saha,** and **Paramesh Gadige.** Thermoresponsive poly (N-isopropylacrylamide) (PNIPAM) particles of different sizes with polydispersities varying over a wide range (8.8%-72.6%) were synthesized using one-pot and semi-batch methods. Size, polydispersity and thermoresponsivity of the PNIPAM particles were characterized using dynamic light scattering (DLS) and compared with scanning electron microscopy (SEM) and cryogenic SEM. Surface charge characteristics of the PNIPAM particles were studied by zeta potential measurements. Stiffness of these particles is observed to increase with increase in particle size. The effects of stiffness and polydispersity on the glass transition of PNIPAM hydrogel suspensions were investigated by rheology. Steady shear viscosity data as a function of volume fraction φ fit well to the Vogel-Fulcher-Tammann (VFT) equation. Stiffer particles with high polydispersity are seen to form fragile glasses at a low critical volume fraction ϕ_c, whereas softer particles with low polydispersity form fragile glasses at higher ϕ_c. The high fragility values observed at higher polydispersities are attributed to the increased prevalence of dynamical heterogeneities. This study demonstrates the tunability of fragility with stiffness and polydispersity of the PNIPAM particles, thereby indicating that these particles are excellent candidates for modelling the dynamics of glass formation.

(iv) **Dynamical heterogeneities in a soft glassy colloidal clay suspension** with **Paramesh Gadige, Debasish Saha.** The dynamics of the Laponite clay system were studied extensively using dynamic light scattering experiments as a function of waiting time (Debasish Saha, Yogesh M. Joshi and Ranjini Bandyopadhyay, Soft Matter, **10** , 3292 (2014)). The intensity auto correlation functions obtained in these experiments are fitted to the sum of exponential and stretched-exponential function. The function is parameterized with the control parameter i.e waiting time (t_w) using modified (with t_w) VFT equation. It is found that the parameterized equation fits well to the experimental data. The fitted curves are differentiated with respect to t_w to obtain three-point correlation functions. The derivative curves or three-point correlation function curves showed a peak close to the structural relaxation time. It is found that the peak height grows with

increasing t_w, suggesting a growth in the size of regions of dynamical heterogeneities in the system or in other words, the number of dynamically correlated particles. The work thus demonstrates the importance of correlated dynamics and their growth in aging Laponite suspensions in explaining the slowdown in the dynamics and the observed fragile behavior.

Within the theme of structure, dynamics and rheology of non-Newtonian fluids, would be **Bandyopadhyay's Falling ball experiments on aging Laponite colloidal suspensions** with collaborators, **Sanjay K. Behera**, **Debasish Saha**, and **Paramesh Gadige.** The settling of an object through a non-Newtonian fluid leads to very interesting observations on Stokesian flows without any terminal velocity. The group has performed falling ball experiments on aging colloidal suspensions of Laponite. Balls with different sizes are dropped into the suspensions having different initial states of structure. An increase in the velocity of the ball as it gets deeper into the fluid is observed. This increment is more pronounced for larger balls and for lower aging i.e. smaller waiting times of the suspensions. A simple rheological model is constructed to explain the experimental results by taking into account

(i) The restructuring and destructuring processes in Laponite and
(ii) The dependence of the viscosity of the suspensions on structure parameter and shear rate.

Bandyopadhyay's interest in active materials reveals itself in her final area of work this year – that of **synthesis and characterization of Janus particles.** Janus particles are surface active colloidal particles. She has synthesized these particles to study the effect of activity on the glass transition of colloidal particles – evidently one of the focal points of the research done by her group. The particles though named active are not organic in nature. They are prepared from polystyrene (PS) microspheres coated with platinum on half of the surface. The platinum half-coating makes the particles active or rather, self-propelled in hydrogen peroxide (H_2O_2) medium. Experiments on the system are in progress especially with an aim at understanding the properties of their active glassy suspensions.

Yashodhan Hatwalne's areas of research interests include phenomenological theories of liquid crystals, membranes and polymer crystallization, structural and topological instabilities in liquid crystals and similar materials broadly classified under soft condensed matter.

During the past year, he has addressed **tubular growth and bead formation in the lyotropic lamellar phase of a lipid** in collaboration with **Tripta Bhatia (RRI) and N.V. Madhusudana (RRI)** [Soft Matter 11, 2015, 2541]. Using fluorescence confocal polarised microscopy (FCPM) to study tubular growth upon hydration of dry DOPC (1,2-dioleoyl-sn-glycero-3-phosphocholine) in water and waterglycerol mixtures, Hatwalne and his collaborators have developed a model to relate the FCPM intensity profiles to the multilamellar structures of the tubules. Insertion of an additional patch inside a tubule was observed to produce a beaded structure, while a straight configuration was retained if the growth was on the outside. Hatwalne uses a simple theoretical model to suggest that reduction in overall curvature energy is the reason that bead formation is taking place on the tubule.

The above project apart, Hatwalne is also pursuing research problems on **structural classification of graphene nanotori and fullenernes with handles**, with **Jaya Kumar A (PhD student, RRI)**, **topological instability in lyotropic smectic-A liquid crystals** again with Jaya Kumar A. (now at IISc), and Rahul Pandit (IISc) and **topological defects in nematic and smectic elastomers**.

Sandeep Kumar's areas of current professional research interests are liquid crystal nanoscience and synthesis and physical studies of liquid crystals.

Under the first theme of liquid crystal nanoscience, in the period during 2015-16 Kumar has prepared, characterized and dispersed a variety of nanoparticles various liquid crystals producing a new class of material called nanocomposites. Physical properties of these nanocomposites have been studied using different techniques.

(i) **Self-assembly of thiolated graphene oxide onto gold surface and in the supramolecular order of discotic liquid crystals** with **V. Lakshminarayanan, (RRI)** [Self-assembly of thiolated graphene oxide onto gold surface and in the supramolecular order of discotic liquid

crystals, Avinash B. Shivanandareddy (PhD Student, RRI), Manish Kumar, V. Lakshminarayanan and Sandeep Kumar, RSC Advances, 2015, 5, 47692-47700]. Graphene oxide when covalently functionalized with thiol molecules to produce thiolated graphene oxide shows interesting behaviour of self-assembly on gold surfaces and in the supramolecular structures of discotic liquid crystals. With **Avinash B. S. (PhD Student, RRI)** and collaborators, **Sandeep Kumar** confirmed the formation of a self-assembled monolayer on the gold surface by electrochemical, XPS, SEM, and grazing angle IR studies. Supramolecular nanocomposites of anthraquinone based discotic liquid crystals with thiolated graphene oxide were characterized using SAXS, POM, DSC and Cryo-SEM. Such self-assembling supramolecular nanocomposites open up new and interesting possibilities for fundamental studies as well as for optoelectronic applications.

(ii) **Gold nanoparticles in plastic columnar discotic liquid crystalline materia**l with Ravindra Dhar's group at Allahabad University [Gold nanoparticles in plastic columnar discotic liquid crystalline material, Mukesh Mishra, Sandeep Kumar, Ravindra Dhar, Thermochimica Acta, 2016 In Press]. The work examines the effect of gold nanoparticles (GNPs) on the thermodynamical, optical and dielectrical parameters of a discotic liquid crystal (DLC) namely hexabutyloxytriphenylene (HAT4). It has been observed that with the increase of GNPs concentration in DLC, composites show two different regions. In the first regions i.e. low concentrations (<1 wt %), columnar hexagonal-isotropic (Colhp-IL) transition temperature and enthalpy (ΔH) decrease rapidly while in the second regions i.e. higher concentrations (>1 wt %) Colhp-IL transition temperature and ΔH remain approximately constant. It has been observed that, in the case of composites having 0.2 and 0.6 wt% of GNPs, conductivity was enhanced but it was poor as compared to the composite having 1.2 wt% of GNPs. For 1.2 wt% of GNPs, conductivity increased by seven orders of magnitude as compared to the DLC. Optical studies suggested that band gap of nanocomposites has decreased due to dispersion of GNPs.

(iii) **Effect of dispersion of CdSe quantum dots on phase transition, electrical and electro-optical properties of 4PP4OB** again with Ravindra Dhar's group[Effect of dispersion of CdSe quantum dots on phase transition, electrical and electro-optical properties of 4PP4OB, U. B. Singh, M. B. Pandey, R. Dhar, R. Verma and S. Kumar, LIQUID CRYSTALS, 2016, In Press]. Kumaret al. prepared composites of a liquid crystalline material, 4-pentylphenyl 4-octyloxybenzoate (4PP4OB) and cadmium selenide quantum dots (CdSe-QDs) and investigated their thermodynamic, electro-optical and dielectric properties. The effect of QDs on transition temperature from isotropic to nematic and nematic to smectic A phases was evaluated in this study. In the nematic phase, the effect of CdSe-QDs inclusion on various display parameters on host liquid crystals was studied while the electrical parameters of the composites, relative permittivity, dielectric anisotropy, dielectric loss and dielectric relaxation, were investigated in both the nematic and smectic phases. The changes in dielectric parameters of the composites are explained in terms of Maier–Meier theory.

(iv) **Fast response in TN liquid-crystal cells: effect of functionalised carbon nanotubes** in collaboration with R. K. Gupta's group at BITS Pilani [Fast response in TN liquid-crystal cells: effect of functionalised carbon nanotubes, Jitendra Kumar, V. Manjuladevi, R.K. Gupta & S. Kumar, LIQUID CRYSTALS, 2016, 43, 488-496]. The optical response time of a nematic liquid crystal (NLC) decreases due to incorporation of carbon nanotubes (CNTs) in the liquid-crystal host. Such reduction is believed to be due to an increase in the elastic constant of the nanotube-doped LC system. In this paper, the authors present the effect on optical response due to doping a NLC with octadecylamine functionalised singlewalled carbon nanotubes (ODA-SWCNT) in a twisted alignment mode. The electro-optic switching amplitude of ODA-SWCNT nanocomposites of NLC decreases compared to pure NLC. A faster response time is observed with an increase in the concentration of ODA-SWCNT in NLC host. A further test of the optical response of pure NLC in a twisted nematic (TN) cell fabricated using mixtures of polyimide (PI) and

ODA-SWCNT as an alignment layer showed that the response time decreased by ~75% in a TN cell fabricated with a mixture of PI and ODA-SWCNT compared to that of a TN cell prepared using a pure PI alignment layer. The presence of ODA-SWCNT in the alignment layer enhances the surface anchoring of the NLC molecules leading to an increase in the elastic constant and a decrease in the optical response time of NLC.

(v) **Cadmium selenide quantum dots to ameliorate the properties of a room temperature discotic liquid crystalline material,** in collaboration with Ravindra Dhar's group [Cadmium selenide quantum dots to ameliorate the properties of a room temperature discotic liquid crystalline material, Neelam Yadav, Sandeep Kumar and Ravindra Dhar, RSC Advances 2015, **5**, 78823-78832]. In this paper, the effect of cadmium selenide quantum dots on a room temperature discotic liquid crystalline material has been studied. These composites were characterized using differential scanning calorimetry, polarizing optical microscopy, impedance spectroscopy and small angle X-ray scattering. It was found that the composite with the lowest concentration of quantum dots enhanced the quasi one-dimensional conductivity of the discotic liquid crystal by five orders of magnitude without altering the columnar hexagonal phase. X-ray scattering results reveal that a decrement in the core–core distance is brought about by the intercalation of quantum dots in between the columns of the discotic liquid crystal matrix. Dielectric spectroscopy shows a relaxation mode in the high frequency region of the pure discotic material as well as in the composites.

(vi) **Effect of silver nano particles on frequency and temperature dependent electrical parameters of a discotic liquid crystalline material,** in collaboration with Ravindra Dhar's group [Effect of silver nano particles on frequency and temperature dependent electrical parameters of a discotic liquid crystalline material, Priti Yaduvanshi, Avneesh Mishra, Sandeep Kumar, Ravindra Dhar, Liq. Cryst. 2015, 42, 1478-1489].In this paper, the effect of silver nanoparticles (AgNPs) of diameters 6 and 100 nm on a discotic liquid crystalline material, namely 2,3,6,7,10,11-hexabutyloxytriphenylene (in short HAT4), has been observed in thermodynamic, electrical and optical texture studies. Silver nanoparticles (0.6 wt %) of diameter ~6 nm demonstrate a negligible (but when the diameter increases to ~100 nm shows appreciable) effect on the broad temperature range plastic columnar hexagonal (Colhex) phase of pure HAT4. The dielectric studies have then been carried out in the frequency range of 10 Hz–35 MHz under homeotropic anchoring conditions of the molecules. In the low frequency region of pure HAT4 and its AgNP composites, a relaxation mode has been observed in these studies. AgNPs of 6 nm also elevate the value of dielectric permittivity of the plastic columnar hexagonal phase of pure HAT4. The dc conductivity of pure HAT4 and its AgNP composite (6 and 100 nm) material has subsequently been determined. Also the optical band gap for pure and AgNP composites of HAT4 has been determined by the ultraviolet-visible study. Due to insertion of AgNPs, the optical band gap of HAT4 has been found to be reduced.

(vii) **Enhancement of the thermodynamic, electrical and optical properties of hexabutyloxytriphenylene due to copper nanoparticles,** in collaboration with Ravindra Dhar's group [Enhancement of the thermodynamic, electrical and optical properties of hexabutyloxytriphenylene due to copper nanoparticles, P. Yaduvanshi, A. Mishra, S. Kumar & R. Dhar, J. Mol. Liq., 208,160–164 (2015)].In the article, the authors have studied the effect of copper nano-particles on the thermal, optical and dielectric parameters of a liquid crystalline material 2,3,6,7,10,11 hexabutyloxytriphenylene (in short HAT4) showing wide temperature range (~65°C) hexatic columnar mesophase. A composite has been prepared by dispersing 0.6 wt. % of copper nano-particles. UV–vis spectroscopy has been used to record the absorption spectra. It has been observed that the presence of copper nano-particles introduces surface plasmon resonance and reduces the optical band gap of HAT4. Though isotropic to mesophase transition temperature is unaffected but mesophase-crystal transition temperature has decreased which implies that the range of the

mesophase has been enhanced due to the presence of copper nano-particles.While dc conductivity has been found to have increased by about two orders of magnitudes, dielectric permittivity has also moderately increased.With this kind of enhanced properties, HAT4-copper nano-particle composite would useful for one dimensional conduction and photovoltaic applications.

(viii) **Tuning Phase Retardation Behaviour of Nematic Liquid Crystal Using Quantum Dots,** in collaboration with R. Manohar's group at Lucknow University [Tuning Phase Retardation Behaviour of Nematic Liquid Crystal Using Quantum Dots, Swadesh Gupta, Dharmendra Singh, R. Manohar, and Sandeep Kumar, Current Appl. Phys. 16, 79-82 (2015)]. The work reports the phase retardation behavior of nematic liquid crystal (NLC) doped with CdSe quantum dot (QD). A study of birefringence and relative permittivity in 4-octyl-40-cyanobiphenyl (8CB) NLC and its variation with doping of QDs has been presented. The study shows improvement of NLC ordering after addition of QDs. The observed higher value of birefringence in QD doped NLC system has been attributed to improved alignment due to additional order in NLC by self assembled QDs. Study of relative permittivity has also revealed the ordering effect in QD dispersed NLC system.

(ix) **Influence of CdSe quantum dot on molecular/ ionic relaxation phenomena and change in physical parameters of ferroelectric liquid crystal,** again in collaboration with R. Manohar's group. Spherical cadmium selenide (CdSe) quantum dots (QDs), capped with octadecylamine, dispersed in ferroelectric liquid crystal (FLC), can remarkably alter the electro-optical (E-O) parameters (material parameters) of the host compound. Here Kumar and his collaborators present an E-O, dielectric, surface anchoring and fluorescence study demonstrating that the physical properties of host FLC strongly depend on the dopant (QD) concentration. The addition of QDs in FLC changes the surface anchoring of FLC molecules, which results the change in E-O parameters of pristine FLC as a function of QDs concentration. The ion–polarisation coupling induces a new temperature-dependent weak ionic relaxation mode (TDWIRM) in FLC–QDs mixture at a certain concentration of QDs. Dipolar coupling between CdSe QDs and FLC molecules readjust the dielectric properties and molecular/ionic relaxation phenomenon in the FLC–QDs mixtures. The fluorescence of FLC–QDs mixtures is probably due to the coupling between the exciton and photon in LC medium, which leads to a radiative process. Further investigation of the fluorescence property of FLC–QDs mixtures reveals that the concentration of uniform-sized QDs only changes the fluorescence intensity of the FLC–QDs mixtures. [Influence of CdSe quantum dot on molecular/ ionic relaxation phenomena and change in physical parameters of ferroelectric liquid crystal, D.P. Singh, Swadesh Kumar Gupta, S. Pandey, Prachi Tripathi , Mahesh Varia, Sandeep Kumar and Rajiv Manohar, Liq. Cryst., 42, 1159-1168 (2015)].

(x) **Effect of octadecylamine functionalized SWCNTs on the elastic constants and electro-optic response of a liquid crystal,** with R. K. Gupta's group**.** As has been amply demonstrated by the aforementioned works of Kumar during the past year, for efficient and high-performance liquid crystal (LC) devices, the physical properties of the LC materials can be suitably altered by incorporating nanomaterials like carbon nanotubes (CNTs), graphene and quantum dots. In the present work, the effect of incorporation of octadecylamine-functionalised single-walled carbon nanotubes (ODA-SWCNT) on the physical properties of a LC exhibiting nematic and smectic phases is investigated. At the lower concentration of ODA-SWCNTs (0.05 wt %), the anchoring of the nanotubes at the LC–electrode interface is favoured. At higher concentration of the ODA-SWCNTs, in addition to the anchoring at the interface, the nanotubes that are dispersed in the LC medium increases the orientational ordering. Moreover, the electro-optic threshold voltage in the nematic phase of ODA-SWCNT nanocomposite of LC is enhanced as compared to that of pure LC. The dielectric anisotropy as a function of reduced temperature decreases with an increase in the concentration of ODA-SWCNT. The ratio of bend to splay elastic

constants of ODA-SWCNT nanocomposite of LC is enhanced considerably as compared to that of pure LC at low temperature. The electrooptic response rise time decreases while decay time increases at higher concentrations of ODA-SWCNT and finally, the temperature range of smectic phase is increased with an increase in the concentration of ODA-SWCNT. [Effect of octadecylamine functionalized SWCNTs on the elastic constants and electro-optic response of a liquid crystal, Jitendra Kumar, V. Manjuladevi, R. K. Gupta, S. Kumar, Liq Cryst, 42, 361-369 (2015)].

Kumar's work on the design, synthesis and physical properties of liquid crystalline materials comprised of the following projects during the past year -

(i) **Synthesis and characterization of novel isoxazole based banana liquid crystal from naturally occurring curcumin** in collaboration with **Arun Roy (RRI)** and **Ashwath Narayana Gowda (PhD student, RRI)**. Isoxazole-based bent-core liquid crystals (LCs) derived from naturally occurring curcumin were synthesised in this work and their LC properties were investigated by polarising optical microscopy, differential scanning calorimetry and X-ray diffraction techniques. Five compounds, including a branched alkyl chain derivative, were prepared and characterised. These derivatives exhibit enantiotropic mesophases. While lower homologues display wide-temperature-range nematic phase, a longer-chain derivative 3d shows smectic C phase in addition to the nematic phase. The bent angle in these compounds is in between calamitic LCs and banana LCs. Therefore, the molecules escape from polar order packing observed in typical bent-core LCs. Increasing the length of alkyl chain reduces both melting and isotropic temperatures in the series. However, the compound with branched alkyl chains exhibits significant reduction only in the nematic-isotropic temperature. Detailed XRD experiments also confirm the presence of the N phase in the lower homologues and SmC phase in a higher homologue. [Synthesis and characterization of novel isoxazole based banana liquid crystal from naturally occurring curcumin, Ashwath Narayana Gowda, Arun Roy and Sandeep Kumar, Liquid Crystals (2016), 43(2), 175-182]

(ii) **Dye-Sensitized Solar Cells with Iodine-free Discotic Electrolytes;** work in collaboration withV. Lakshminarayanan (RRI). Discotic mesogenic molecules viz., hexahexylthiotriphenylene (HHTT) and hexahexyloxytriphenylene were applied, for the first time, as an iodine-free redox electrolyte in dye-sensitised solar cells (DSSCs). The cell showed open circuit voltage (Voc) of 0.95 V, short circuit current density (Jsc) of 0.534 mA/cm^2, fill factor 88.24% and overall power conversion efficiency (η) 0.45% in a typical fluorine doped tin oxide / TiO2 / N719 / HHTT / Pt DSSC configuration. Scanning electron microscopy was used to study surface profile of electrolytes while electrochemical impedance spectroscopy was used to understand the electrochemical behaviour of electrolytes. The photovoltaic parameters were measured under standard conditions using Oriel solar simulator class AAA. These first results demonstrate the potential of the discotic molecules as charge transporter and mediator and show promise to be used in iodine-free DSSCs. [Dye-Sensitized Solar Cells with Iodine-free Discotic Electrolytes, Ananda Rama Krishnan Selvaraj, V. Lakshminarayanan, Ravindra Dhar and Sandeep Kumar,Liq. Cryst., 42, 1815-1822 (2015)].

(iii) **Electron transporting organic materials with an exceptional large scale homeotropic molecular orientation,** in collaboration with Zhiqun He's group (Beijing Jiaotong University, China). An electron transporting anthraquinone derivative has demonstrated a stable large-scale homeotropic alignment on an open substrate surface, which substantially improved its charge carrier mobility. The electron mobility (mE) was observed to have increased by two orders of magnitude from 3.2 X 10^{-4} cm^2 V^{-1} s^{-1} for the film without alignment to 1.2 X 10^{-2} cm^2 V^{-1} s^{-1} for the homeotropically aligned film. A distinct enhancement in the UV absorption spectra of the films around the short wavelength range was observed to be associated with the molecular alignments but the point of interest was that these alignments are less sensitive to the substrate under test. The anchoring force of the

columnar stacks may be related to the nature of the material associated with the strong interaction between the molecules and substrate interface. [Electron transporting organic materials with an exceptional large scale homeotropic molecular orientation, Huan Zhao, Zhiqun He, Min Xu, Chunjun Liang and Sandeep Kumar, Phys.Chem.Chem.Phys. 2016, 18, 8554].

(iv) **Tailoring of Cholesteric Plane Spacing, Dielectric Relaxation and Optical Properties of High Temperature Chiral Nematic Phase by UV Irradiation,** with R. Manohar's group**.** The effect of Ultra Violet (UV) irradiation on the high temperature chiral nematic (N∗) mesophase has been investigated in this paper. The controlled UV exposure produced bending in rod shape molecules. The bending of molecules affects their long molecular axis; therefore, the relaxation mode associated with the rotation of molecules along the long molecular axis shifts toward the higher frequency. The UV irradiation also increases the cholesteric plane spacing of N∗LC molecules while the a.c. conductivity of N∗LC increases enormously after the UV irradiation. The efficiency of opto-dielectric effect has also been evaluated with the variation of bias voltage in the present investigation. [Tailoring of Cholesteric Plane Spacing, Dielectric Relaxation and Optical Properties of High Temperature Chiral Nematic Phase by UV Irradiation, Dharmendra Pratap singh, Tripti Vimal, Swadesh Kumar Gupta, Prachi Tripathi, M. C. Varia, Sandeep Kumar, Shashwati Manohar, and Rajiv Manohar, Mol. Cryst. Liq. Cryst. 2016, 625, 1-10].

(v) **Bulk hetero junction solar cell based on self assembling of disc shaped liquid crystalline material,** in collaboration with the Ravindra Dhar's group. In this article, the effect of addition of a disc-shaped liquid crystalline material, namely 2, 3, 6, 7, 10, 11-hexabutyloxytriphenylene, in poly (3-hexylthiophene): [6, 6]-phenyl-C61-butyric acid methyl ester containing bulk heterojunction (BHJ) solar cells has been investigated. These disc-shaped molecules organize into ordered columnar hexagonal structures through intermolecular $\pi - \pi$ interactions as monitored by polarised light optical microscopy. Current–voltage characteristics of the device prepared with this liquid crystal layer exhibited a short-circuit current of 10.5 mA cm^{-2} and a fill factor of 35%. The resultant power conversion efficiency (PCE) was 1.54%. The influence of varying the thickness of liquid crystal layer and an additional annealing step, on these solar cells was also studied. The short circuit current and PCE of 12.9 mA cm^{-2} and 2.3% were achieved for these BHJ solar cells containing self-organised discotic liquid crystals in the active layer under one sun condition after annealing. [Bulk hetero junction solar cell based on self assembling of disc shaped liquid crystalline material, Maneesha Bajpai, Neelam Yadav, Sandeep Kumar and Ravindra Dhar, Liq. Cryst. 2016, 43, 305-316].

(vi) **Solvatochromism of tricycloquinazoline based disc-shaped liquid crystal: A potential molecular probe for fluorescence imaging,** work in collaboration with R. K. Gupta group. Tricycloquinazoline (TCQ) based discotic liquid crystals (DLCs) were found to be fluorescent in nature. Such molecules can be employed for the fluorescence imaging of another DLC. Therefore, it is essential to study systematically the photophysical properties of such molecules. In this article, the authors report the effect of solvents on the photophysical properties of DLC molecules possessing a central TCQ core covalently linked to 6 ethelenoxy side chains (TCQDL molecules). The solutions of TCQDL are prepared in organic solvents of different polarity. The solutions are then scanned using ultraviolet-visible (UV-Vis) and fluorescence spectrophotometers. The excited state dipole moment of the TCQDL molecule is estimated from the data. The ground state dipole moment of the TCQDL molecule is calculated using Gaussian 03. The observations are that that the TCQDL molecule can be used as a fluorophore and used to image other non-fluorescent DLC systems. The epifluorescence imaging of the Langmuir monolayer of the pure TCQDL molecules at the air–water interface showed good image contrast allowing the identification of surface phases even in the absence of additive fluorescent probe molecules. [Solvatochromism of tricycloquinazoline based disk-shaped liquid

crystal: A potential molecular probe for fluorescence imaging, C. Karthik, Manjuladevi V., Raj Kumar Gupta and Sandeep Kumar, RSC Adv., 2015, 5, 84592].

(vii) **Synthesis of new U-shaped azobenzene liquid crystals for photoswitching properties**, work done with collaborator, Md Lutfor Rahman (University of Malaysia, Pahang). A new series of liquid crystalline compounds comprising a U-shaped unit as central core incorporating azobenzene in the side arms and having terminal alkene functional groups, is synthesized and characterized by differential scanning calorimetry (DSC), polarized-light optical microscopy (POM), X-ray diffraction analysis and UV-vis spectroscopy. In the U-shaped series, all compounds showed stable enantiotropic monolayer SmA phases independent on the chain length and chain parity. These U-shaped molecules exhibit strong photoisomerisation behaviour in solutions and in solid state. The photoswitching properties of compounds showed trans to cis isomerization in about 15 seconds, whereas the reverse process required much longer times ranging from 235–380 min in solutions. In case of solid film of 4a, E–Z photoisomerization takes around 4 s and the reverse transformation to original Z–E state takes about 74 min. The kinetic study using UV light irradiation shows that all compounds (4a–e) behave according to the first order rate law throughout the relaxation time in solution. The effect of alkyl chain length for trans to cis is negligible whereas, cis to trans is substantial on the odd–even chain length. The photoisomerization study with variable light intensities shows that the photosaturation and thermal back relaxation times are decreased when intensity of the irradiated light is increased. In fact, the compounds did not degrade at all with light illumination at 10 mW cm^{-2}. The reversible isomerization though did not significantly decay after multiple cycles indicating that the photo-responsive properties are stable and repeatable. Thus, the photoswitching behaviour of these materials could be suitably exploited in the field of optical data storage device and in molecular switches for suitable switching times. [Synthesis of new U-shaped azobenzene liquid crystals for photoswitching properties, Md Lutfor Rahman, Shaheen M. Sarkar, Mashitah M. Yusoff, Sandeep Kumar and Carsten Tschierske, RSC Adv., 2015, 5, 87019].

(viii) **The Chemistry of Bent-Core Molecules forming Nematic Liquid Crystals.** Analogous to rod-shaped and disc-shaped molecules, bent-core molecules also exhibit nematic phases, in addition to other higher order mesophases. Presently, about 600 bent-core or banana-shaped molecules are known to exhibit nematic phases. In this work done with **A. N. Gowda (PhD student, RRI),** the chemistry and mesomorphic properties of all these materials are summarized. [The Chemistry of Bent-Core Molecules forming Nematic Liquid Crystals, Sandeep Kumar, A.N. Gowda, Liq. Cryst. Rev., 3, 99-103 (2015)].

(ix) **Charge transport in a liquid crystalline triphenylene polymer monolayer at air-solid interface,** in collaborating with K. A. Suresh (CNSMR, Bangalore). Kumar *et al.* have prepared a monolayer of a novel liquid crystalline polymer derived from 2,6-dihydroxy-3,7,10,11-tetraalkoxy-triphenylene (PHAT) at air-water interface and transferred it onto freshly cleaved mica as well as onto gold coated mica substrates using the Langmuir-Blodgett (L-B) technique. The atomic force microscope (AFM) images of these L-B films show a uniform coverage with thickness of 1.5 nm. Electrical conductivity measurements were subsequently carried out on the PHAT monolayer deposited on the gold coated mica substrate using a current sensing AFM (CSAFM). The gold substrate−PHAT monolayer−cantilever tip of CSAFM, form a metal−insulator−metal (M-I-M) junction. The CSAFM yields a non-linear current−voltage (I−V) curve for the M-I-M junction. The analysis of the I−V characteristics of the M-I-M junction indicated that the charge transport in the liquid crystalline polymer monolayer happens by direct tunneling mechanism. The barrier height for the PHAT monolayer was estimated to be 1.22±0.02 eV. [Charge transport in a liquid crystalline triphenylene polymer monolayer at air-solid interface, H. N. Gayathri, Bharat Kumar, K. A. Suresh, H. K. Bisoyi and Sandeep Kumar, Phys.Chem.Chem.Phys. 2016 In Press].

Pramod Pullarkat's areas of current professional research interests are in studying mechanical properties of axons, which are thin tubular extensions produced by neuronal cells in order to conduct electrical signals, stabilities of axonal shapes, effect of shear stress on cells and membrane tether mechanics as a model for understanding filopodial dynamics.

Axons are thin tubular extensions produced by neuronal cells in order to conduct electrical signals. In a human body they can be anything from a few tens of microns (in the brain) up to a meter long (in nerves extending into lower limbs). The diameter of the axon is only about a micron and in normal cells it is almost constant for the entire length. This robustness may be because the diameter is set by interplay of opposing physical factors. For example, the axonal membrane tension which tries to reduce the diameter and the entropic internal pressure due to the polymer gel that fills the interior (cytoskeleton). Moreover, maintenance of axonal plasticity (flexibility of the axon towards physical cues for any rewiring) requires that the neuronal cell should be able to retract and reform connections. Here it is suspected that molecular motors and polymer dynamics are at work as they can generate stresses and flows to actively remodel the cytoskeletal structure. How do axons maintain a constant diameter over such long lengths? What determines the generation and redistribution of components during axonal growth? What drives the retraction of axons during axonal rewiring? These are some of the questions Pullarkat and his team have been trying to address.

Apart from these, the group also investigates active axonal membrane dynamics and mechanics using an in-house built optical Tweezer setup.

The lab's approach includes development of simple assays, image analysis techniques and fluorescence microscopy methods, use of genetic and biochemical tools, etc. In the absence of readily available, pre-designed apparatus that are needed for some of these quantitative analyses, the group also devotes time to the development of new tools. They have already developed a new type of force apparatus, which can measure with pico-Newton and nano-meter precisions, for which a patent has been applied for. During the past year, they have also designed and fabricated a compact device to apply rotational fluid shear stress to cells in order to quantify cell adhesion properties.

The group believes in an interdisciplinary approach to these problems and thus the work involves deep collaborations with neurobiologists at IISER-Pune and theoretical physicists at Institut Curie, Paris.

(i) Under the research theme of **probing mechanical properties of axons**, is Pullarkat's work with **Sushil Dubey (PhD student, RRI)**. They have performed rheological measurements on axons using the constant-strain mode that has been implemented into the force device mentioned above. The data shows that detachment dynamics of protein crosslinks is central to the dissipative behaviour (viscoelasticity) in axons. Using biochemical means, they have shown that cortical actin (a specialized layer of cytoplasmic protein under the periphery of the cell membrane of the neuronal cell that typically helps in maintaining cell tension) in axon has a significant mechanical role. However from previously known observations, actin is not a major cytoskeletal component of the axon when compared with microtubules. Some recent reports based on super-resolution microscopy show that axonal actin organises in the form of periodic rings interconnected by spectrin. This could give rise to a crystal-like elasticity to axons instead of a viscoelastic response. With collaborators Dubey, Deepak Nair (IISc), Aurnab Ghose (IISER-Pune and Andrew Callan Jones (University-Paris, Diderot), Pullarkat is conducting super-resolution imaging of these cells to verify the actin structure.

(ii) Using specific biochemical agents to depolymerise actin-filaments or microtubules (biopolymers present inside the axon) the group has studied the resulting shape evolution of an axon or rather **shape instabilities in axon.** Pullarkat has collaborated with Anagha Datar (former PhD student, RRI), Roli Srivastava (Project Assistant, RRI) and Alka Bhat (VSP student, RRI) for these experiments. He is now trying to develop theoretical models for the experimental results with help from Jacques Prost (Institut Curie, Paris).

(iii) **Cell adhesion studied using an in-house developed and built shear device –** Pullarkat and **Renu Vishavkarma (PhD student, RRI)** have developed a shear device for studying the

effect of shear stress on cells along with fluorescence microscopy. The device itself is novel - it is made using a computer hard-disk motor which provides superb wobble-free performance, is very compact and hence mountable on any standard microscope including confocal systems. Vishavkarma has shown that this device can differentiate changes in adhesion and it can also be used along with micro-patterning to create well defined cell geometries. She has shown that cell adhesion can be quantitatively studied by measuring accurately the cell detachment under either a constant shear as a function of time or as a function of shear stress. Pullarkat and Gautam Menon (IMSc) are working on a theoretical model to support their excellent experimental data. An extension of Vishavkarma's work in the form of a collaborative project with Namrata Gundiah (IISc) and Gautam Menon is also under way.

(iv) **Membrane tether mechanics** - Using the Optical Tweezers setup developed at RRI by Susav Pradhan (VSP student, Research Assistant, RRI) Pullarkat, Pradhan and **Renu Vishavkarma (PhD student, RRI)** have performed a few 'tether' experiments on axonal cells to understand better how a tether is retrieved back into the neuronal cell body. This has not yet been explored and runs counter to various prevalent theories of membrane mechanics. In fact, Pradhan has conducted a series of experiments showing that membrane tethers pulled out of axons of neuronal cells can be used as model systems to study filopodial dynamics. Filopodia are tube like extensions generated by motile cells utilising polymerisation forces generated by actin bundles and used for cell motility. The mechanism for filopodial dynamics-growth, contractility and retraction-is not well understood. This model system exhibits all major filopodia-like dynamics and is conducive to quantitative measurements of forces. The first phase of this work is nearing completion. Pradhan has also done a series of experiments to measure cell membrane tension as part of collaboration with Satyajit Mayor's (NCBS) lab.

Pratibha R.'s areas of current professional research interests include chirality, electric field induced phase transitions, defects and patterns in liquid crystals, dielectric properties of polyelectrolytes, and functional liquid crystal composites.

During the period 2015-16, Pratibha has been engaged in a **study of the synchronization of conformational chirality in liquid crystals made up of achiral molecules.** Her collaborator in this project was Anjali S. (VSP student, RRI).

Mirror symmetry breaking is observed in a variety of systems ranging from naturally occurring bio-molecules to liquid crystals formed of achiral molecules. From a technological point of view, realizing stable and selective homochirality can have technological implications for non-linear and chiroptical applications. It is therefore of interest to investigate the origin of spontaneous deracemization and find methods to stabilize chiral segregation. Molecular conformational chirality has often been proposed as a possible driving force for chiral symmetry breaking in achiral fluids, with deracemization being initiated by segregation of enantiomeric conformers. Incidentally bent-core liquid crystals (BCLCs) composed of achiral molecules have the special property of generating layer chirality arising from a combination of director tilt and polar order. Simulations and NMR studies have shown that most often the BC molecules adopt chiral conformations around the central aromatic core. In the lamellar phases of BCLCs, it is therefore possible for identical conformers to arrange themselves such that their enantiomeric excess (ee) and hence the chiral sense within the layers, can be biased. These LCs are therefore ideal candidates to investigate the role of conformational chirality. This is very well illustrated in the dark conglomerate (DC) phase formed by BC molecules where the enhanced efficiency of packing of identical chiral conformers cannot be sustained beyond a certain limit in flat layers and results in layer deformation. Based on detailed freeze fracture studies, it has been proposed that layer frustration in the DC phase is relieved by saddle-splay layer deformation resulting in focal conic domains with negative Gaussian curvature. But usually, complete deracemization is difficult to achieve in fluids, as molecular conformations keep varying and chiral segregation cannot be sustained over extended periods of time.

The group has recently undertaken studies to show thatee of conformers and thus deracemization, can be controlled by mixing two types of BCLCs both composed of molecules possessing conformational chirality. This strategy also provides a method to progressively monitor the synchronization of conformational chirality between the two molecules that can lead to chiral segregation. The concentration dependent progression of deracemization has been monitored by optical, dielectric and electro-optic studies and the layer profiles visualized by scanning electron microscopy (SEM).

Two BCLCs, viz. 2,7- naphthylene bis[4-(3-methyl-4-n- tetradecyloxybenzoyloxy)] benzoate (NMTBB) with a central naphthylene core which forms DC phases under electric fields and 1,3-phenylene-bis[4-(3-methylbenzoyloxy)]-4'-n-dodecylbiphenyl-4'-carboxylate (PDMBC) with a central phenyl ring and exhibiting a well characterized lamellar SmCP phase, were used for the study. The lowest energy conformers obtained by calculation of conformational energies using a molecular mechanics force field (MMFF) model showed a pronounced chiral conformation about the central aromatic unit in the case of both NMTBB and PDMBC molecules. Three types of lamellar mesophases were observed depending on the relative concentration of the two BCLCs. The dark enantiomeric (DE) phase with a single homochiral domain was obtained with concentrations of PDMBC up to 20wt% (Region 1) and the dark conglomerate (DC) phase characterized by macroscopic homochiral domains of opposite handedness was found in regions with 20-50wt% (Region 2) of PDMBC. Further increase in concentration of PDMBC resulted in the formation of the birefringent lamellar SmCP phase (Region 3). Layer profiles as visualized with SEM showed large areas with aligned flat smectic layers in PDMBC and disordered arrays of deformed layers in mixtures M20 and M50 with 20 and 50 wt% of PDMBC. The deformation wavelength was found to be smaller in M20 than in M50 indicating that layer deformation and compactness of the sponge-like layer structure was more severe in M20. This is consistent with the fact that Region 1 with mainly NMTBB molecules has an abundance of enantiomeric conformers of one type decided by the combination of lowest energy conformer type of NMTBB and the spontaneous polarization and tilt angle. The frustration within the layers is therefore enhanced leading to stronger layer distortion and hence decrease in the wavelength of deformation. On the other hand in Region 2 having appreciable amounts of both PDMBC and NMTBB, synchronization between the molecular conformations of the NMTBB and PDMBC molecules is less efficient and it is more favourable for left and right handed conformers to segregate and form homochiral domains of opposite handedness. In Region 3 the conformer packing efficiency is further decreased as both NMTBB and PDMBC molecules are present in comparable numbers and the steric hindrance between them is increased even more resulting in the formation of the SmCP phase with flat layers.

Their earlier work had shown that molecular motions are impeded within deformed layers. As a result dielectric response can be used to obtain information about the severity of layer deformation. On measuring the dielectric parameters the value of the static permittivity ε was found to be highest in the SmCP phase of PDMBC with flat layers where molecular rotations are not hampered much, and progressively reduced in the mixtures, as the conformer packing efficiency increased and the layer deformation became more severe. The high frequency mode associated with reorientation about the long (bow) axes of the BC molecules was prominent in PDMBC with flat layers and in concentration regions where deformation is less severe as the molecular reorientation is easier and collective motion is less rigorous. On the other hand in the low concentration regions of PDMBC where deformation wavelength is smaller and coupling of enantiomeric conformers is more efficient, the dielectric strength of the low frequency mode originating from the collective motion associated with the homochiral domains was observed to be higher than that of the high frequency mode. The electro-optic switching was also in support of this, requiring a much higher voltage in the DE phase with stronger layer deformation as easy reorientation of the polarization is difficult. On the other hand in the DC phase where conformer packing efficiency is somewhat reduced and layer deformation is less severe, the electro-optic response was observed at relatively lower voltages.

The progressive evolution of homochirality as a function of the relative concentration of the achiral constituents as observed in the present binary system clearly shows the role of an intrinsic coupling of molecular conformational chirality. Such a correlation between the detailed structure and physical properties has not been previously established in these frustrated mesophases and serves as a model system for understanding chirality synchronization even with relatively large and flexible achiral molecules. This technique can also provide a new paradigm for tuning and controlling macroscopic chirality and for optimizing chiroptical properties for applications.

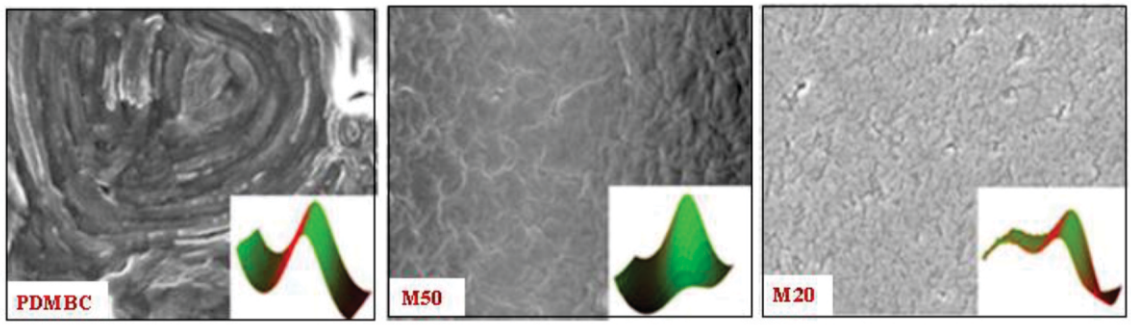


Fig. 1

Fig1. SEM images and imaginary part of permittivity in the lamellar phases of PDMBC with flat layers and M50 and M20 with weak and strong layer deformation. [Image courtesy - **Synchronization of conformational chirality in mixtures of achiral bent-core molecules,** S. Anjali and R. Pratibha, RSC Advances (under Review)].

Pratibha's second major research endeavour during the year gone by has been **an investigation of the unusual occurrence of a reentrant lamellar phase in bent-core liquid crystals** in collaboration with **Pramod Tadapatri, (Postdoctoral fellow, RRI)**, Smruti Rekha Mahapatra (VSP student, RRI), and **B.K Sadashiva (RRI)**.

Bent-core liquid crystals (BCLCs) exhibit lamellar SmCP phases in which a coupling of the molecular tilt about the arrow axis and polar ordering within the layers, leads to layer chirality.The structure of the SmCP phase depends on the stacking of the bent molecules in adjacent smectic layers. Both homochiral ($SmC_AP_A$and SmC_SP_F) and racemic ($SmC_SP_A$and SmC_AP_F) versions are possible. Here the subscripts A and S of C refer to anticlinic and synclinic tilting and the subscripts A and F of P refer to antiferroelectric and ferroelectric polar order between adjacent layers. The packing of these BC molecules which possess a highly polar shape and large bend angle of ~120°, results in spontaneous transverse polarization. Most often the SmCP phases exhibit electro-optic switching. As the sample temperature is decreased, sometimes a phenomenon called phase reentrance is observed. Phase reentrance is nothing but a state where a less ordered phase characteristic of a higher temperature reappears again below a more ordered one at the lower temperature. This is extremely rare in the case of BCLCs and very few examples are known. Pratibha et al. in their experiment below have been able to demonstrate this very phenomenon.

The group's recent studies on a homologous series of achiral seven-ring bent-core compounds derived from 5-methoxyisophthalic acid shows that the middle homologues exhibit two lamellar phases in the same compound. While a direct phase transition between the lamellar phases can be observed in the homologue with alkyl chain length n=11, the next higher homologues with n=12 to 16 exhibit two lamellar phases separated by another mesophase with an additional two dimensional periodicity. Electro-optic and dielectric studies distinguish the phase transitions and show clear evidence for the reentrant lamellar phase. The polar switching characteristics of the higher and lower temperature lamellar phases are different indicating that the detailed structure in the two lamellar phases is different. X-ray diffraction studies are now being carried out in order to finally establish this difference in a foolproof manner. They will also help uncover the structure of theintervening phase with the reentrant behavior.

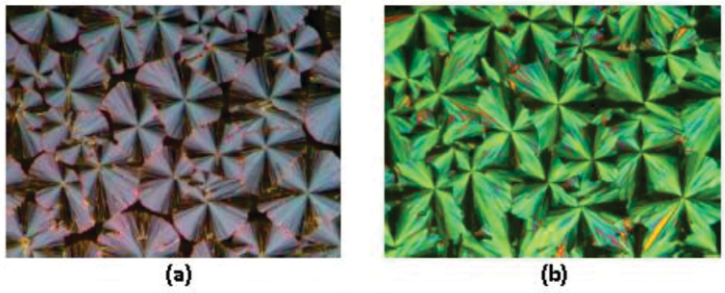


Fig. 2

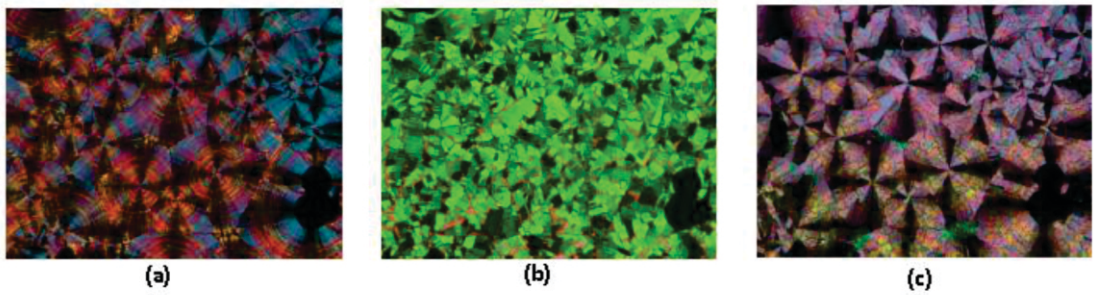


Fig. 3

Figure 2: Occurrence of two lamellar SmCP phases in the 11th homologue of the series of bent-core compounds derived from 5-methoxyisophthalic acid (a) 170^{0}C and (b) 150^{0}C.

Figure 3: Reentrant lamellar SmCP phase formed by the 12th homologue of the same series mentioned in Fig.2 (a) SmCP at 160^{0}C, (b) Mesophase with 2D periodicity at 130^{0}C and (c) reentrant SmCP phase at 115^{0}C.

V. A. Raghunathan is primarily interested in shape changes of membranes induced by binding macromolecules, modification of lipid membrane properties by sterols and adsorbed polymers, mechanical properties and phase behaviour of lipid-sterol membranes, phase behavior of ionic amphiphiles with strongly bound counter-ions and polyelectrolytes, organization of mononucleotides on lipid membranes among other questions in soft condensed matter physics.

Interestingly, many of these problems that Raghunathan endeavours to address can be logically progressed into finding analogues in the biophysical context as well.

During the year gone by, Raghunathan has looked into the **adsorption of polyelectrolytes on charged surfaces** in collaboration with **Meera Thomas (PhD student, RRI)**. Adsorption of polyelectrolytes - charged polymers - on oppositely charged surfaces is important in biology and in many industrial applications (in this case, adhesion of polymer ions on a surface, usually solid, results in the formation of a thin film). In spite of a large number of experimental and theoretical studies, many aspects of this adsorption process are still poorly understood. Raghunathan and Thomas have studied this adsorption process using a periodic stack of charged surfactant bilayers, instead of a single charged surface used in earlier experiments. The set-up is thus conducive to probes such as the standard small-angle x-ray scattering technique. Their results showed that a novel swelling transition in the system can lead to an abrupt increase in the bilayer stacking periodicity. The group is currently investigating the mechanism that could drive this transition.

Raghunathan's second major project in the past year has been the **organization of mononucleotides on lipid membranes** in collaboration with **Sreeja Sasidharan, (Ph.D student, RRI)** and Sudha Rajmani, (IISER, Pune). A fundamental problem in biology is the formation of self-replicating RNA-like polymers. In this connection it has been suggested that such polymers can be synthesized non-enzymatically from mononucleotides in a lipid environment. Motivated by this the group has studied the organization of mononucleotides on lipid membranes. Their experiments show that that these molecules form dense patches on the membrane surface,

which is interesting since such an arrangement is a prerequisite for their polymerization into long chains. Presently Raghunathan *et al* are trying to understand the nucleotide-lipid interaction that would be responsible for the formation of such dense patches.

Arun Roy's professional research interests primarily lie in the broad field of **s**oft condensed matter physics and more specifically in phase transitions, electro-optics of liquid crystals, liquid crystal- nano-particle composites, Micro-Raman spectroscopy and phenomenological theories of liquid crystals.

Under the theme of phase transition and electro-optics of liquid crystals, Roy's research in the past year comprised of investigating the following problems -

(i) **Pseudo-polar tilted smectic phases exhibited by bent core hockey stick shaped molecules,** where he has collaborated with **Deepshika Malkar (PhD student, RRI)** and **B. K. Sadashiva (RRI).** The study of supramolecular self assembly of the constituent molecules is crucial for the development of advanced functional materials if one takes the bottoms up approach. In particular the self organised fluid phases of anisotropic organic molecules of different shapes are an active area of research in soft condensed mater physics. In the year gone by, Roy has studied both experimentally and theoretically two new achiral fluid lamellar phases exhibited by bent-core hockey stick shaped molecules.

A bent core (BC) molecule consists of a relatively rigid central part in which two rod-like arms join end to end making an angle of about 120 degrees between them. In addition, flexible aliphatic chains are usually attached to one or both ends of the rigid core of the molecule. In a symmetric bent core molecule, both the arms and the chains are same, giving rise to the C_{2v} point symmetry of the molecules. Since the discovery of symmetric BC molecules showing plane polar order in their smectic phases, the mesophase properties of such molecules have been explored in great detail. Over and above plane polar order though, the existence of sufficiently large transverse shape polarity of the symmetric BC molecules often leads to chirality in their tilted smectic phases even though the constituent molecules themselves are achiral. Also they show many liquid crystalline phases with properties very different from that exhibited by rod-like or disc-like molecules have been observed. Even the existence of a lowest symmetry fluid lamellar phase with triclinic C_1 point symmetry of the layers has been reported.

A bent-core hockey sticks (BCHS) shaped molecule is formed when one of the arms is relatively shorter than the other arm of the BC molecule. In this work, Roy and his collaborators have studied a compound consisting of BCHS molecules (see fig. 1a below) synthesized in their chemistry laboratory. The differential colorimetric studies as shown in fig. 1b below confirm the existence of the two new liquid crystalline phases between the isotropic liquid and the crystal phase.

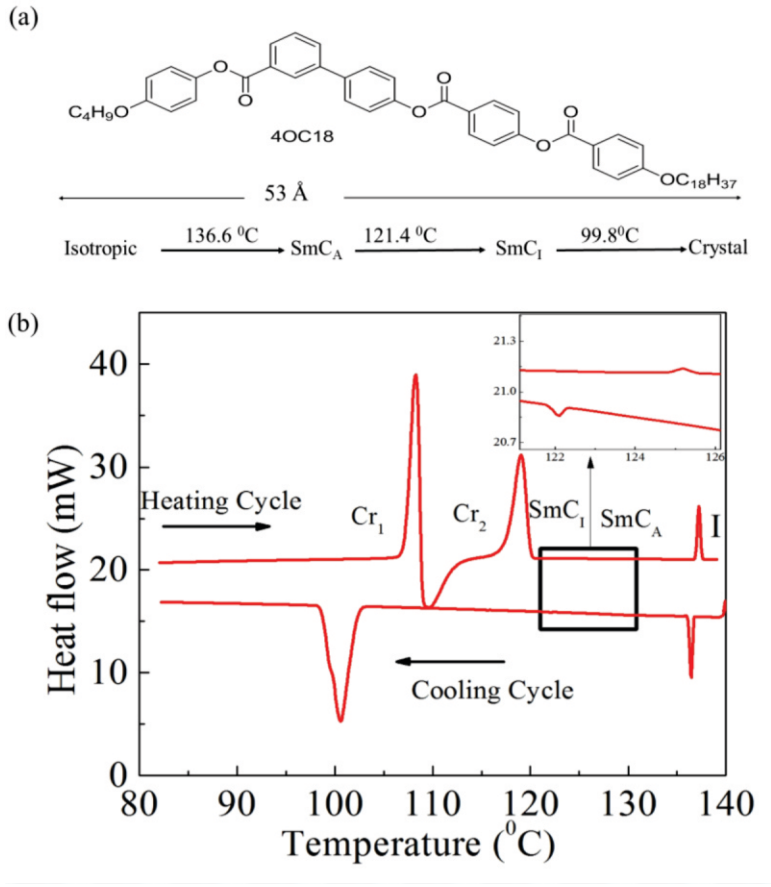


Fig. 1 (a) The molecular structure of the BCHS compound studied and the phase sequence observed on cooling the sample from the isotropic phase. (b) The DSC thermogram of the BCHS compound on heating and cooling at a rate of 5^{0}C/min.

The new liquid crystalline phases were further characterised using X-ray diffraction, polarised optical microscopy (POM) and electro-optic studies. The POM textures of the samples in these new phases confirm the tilted organisation of molecules in the layers.

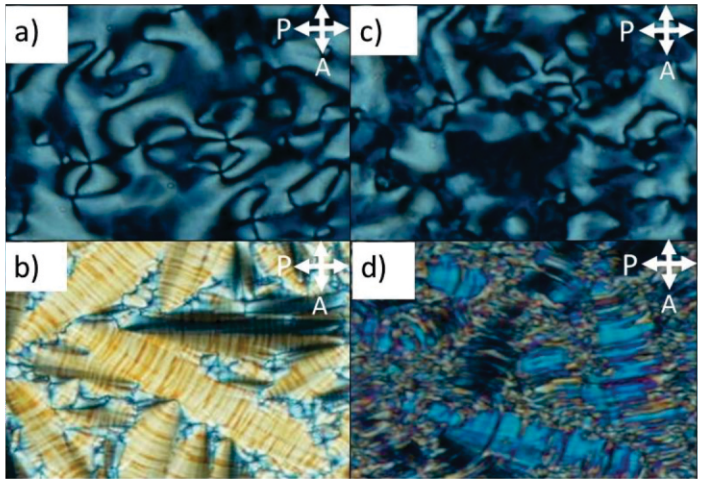


Fig. 2: The POM textures of the BCHS compound in the SmC_A phase at 125^{0}C for (a) homeotropic alignment, (b) planar alignment and in the SmC_I phase at 115^{0}C for (c) homeotropic alignment (d) planar alignment.

Both of these smectic phases show strong electro optic response, which can be exploited for potential applications. Roy and his collaborators also propose that the packing of these bent-core hockey stick shaped molecules in the layers leads to a pseudo-polar order in these tilted smectic phases. An anticlinic SmC_A type stacking of the pseudo-polar layers could be expected in the higher temperature smectic phase, while in the lower temperature phase the difference in the azimuthal angles of the tilt directions in successive layers is between zero and π with a randomized tilt organization between the successive layers. The randomness arises due to the sign degeneracy of the azimuthal angle difference of the tilt directions in successive layers. The proposed model structures of the phases are shown below in Fig.3.

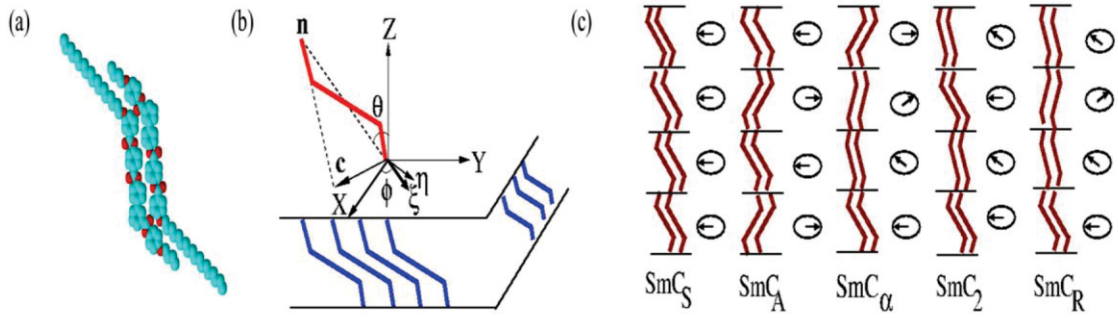


Fig. 3 (a) The zigzag configuration of the molecules within the layer. (b) The pseudo polar tilted organization of the BCHS molecules in the layer. (c) The schematic representation of the predicted structures in the different phases.

The results have been accepted for publication in Soft Matter (2016). [Images Courtesy - **Pseudo-polar tilted smectic phases exhibited by bent core hockey stick shaped molecules**, Deepshika Malkar, B. K. Sadashiva and Arun Roy, accepted for publication, **Soft Matter 2016**].

(ii) **Monolayer to Interdigitated Partial Bilayer Smectic C Transition in Thiophene-Based Spacer Mesogens,** where he has collaborated withM. Kesava Reddy (Central leather research Institute, Chennai), E. Varathan (Central leather research Institute, Chennai), Nitin P. Lobo (Central leather research Institute, Chennai), T. Narasimhaswami Group (Central leather research Institute, Chennai) and K. V. Ramanathan (Indian Institute of Science, Bangalore). Molecular mesogens containing flexible spacers commonly known as dimers, trimers, and oligomers have gained importance in view of their unusual mesophase characteristics. The construction of dimers/oligomers follows the principle of connecting two or more rigid cores through flexible spacers with terminal alkoxy chains at both the ends. The group has investigated the organization of molecules built with thiophene at the center and linked via flexible spacers to rigid side arm core units and terminal alkoxy chains in their liquid crystalline phases. Thirty homologues realized by varying the span of the spacers as well as the length of the terminal chains have been studied. In addition to the enantiotropic nematic phase observed for all the mesogens, the increase of the spacer as well as the terminal chain lengths resulted in the smectic C phase. The molecular organization in the smectic phase as investigated by temperature dependent X-ray diffraction measurements revealed an interesting behavior that depended on the length of the spacer vis-a-vis the length of the terminal chain. A tilted interdigitated partial bilayer organization was observed for molecules with a shorter spacer length, while a tilted monolayer arrangement was observed for those with a longer spacer length. But as a next step, the high-resolution solid state 13 C NMR studies carried out for representative mesogens indicated a U-shape for all the molecules, indicating that intermolecular interactions and molecular dynamics rather than molecular shape are responsible for the observed behavior. Models for the mesophase organization have been considered and the results understood in terms of segregation of incompatible parts of the mesogens combined with steric frustration

leading to the observed lamellar order. The molecular conformation, 2D NMR spectra of one representative compound and the mesophase structures are shown below in fig. 4.

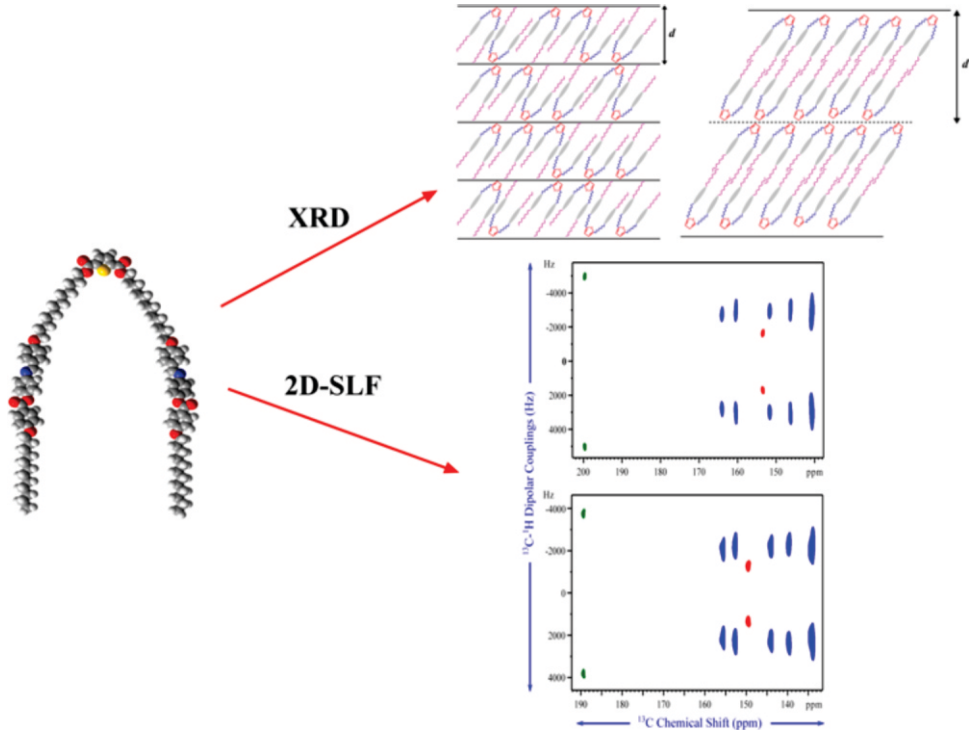


Figure 4: Molecular conformation, 2D NMR spectra and the molecular organisation in the smectic phases of the Thiophene-Based Spacer Mesogens.

(iii) **Synthesis and characterisation of novel isoxazole-based banana liquid crystals from naturally occurring curcumin,** in collaboration with **Ashwath Narayana Gowda (PhD student, RRI)** and **Sandeep Kumar (RRI).** Curcumin is a medicinal natural product, which can be isolated from the rhizome of Curcuma longa L. (Zingiberaceae family). Because of its biological activities, a number of curcumin derivatives have been prepared and studied by the team. [Synthesis and characterisation of novel isoxazole based banana liquid crystals from naturally occurring curcumin, Ashwath Narayana Gowda, Arun Roy and Sandeep Kumar, Liq. Cryst., 43, 175-182 (2016)].

Roy's usage of RRI instrumentation has helped him make progress on a biomedical project that he has embarked upon last year. This would be his work on the **biophysical, biochemical, electron microscopic and histopathological characterization of a Femoral Head bone disease,** in collaboration with Aswath Narayanan, Ritesh N Bhoskar, Venketesh Sivaramakrishna, Sai Muthu Kumar, Prakash Khanchandani (all with Sri Sathya Sai Institute for Higher Learning, Puttaparthy, India.), Chandrashekar Ambati (Indian Institute for Chemical Technology, Hyderabad), Xu Han (Baylor College of Medicine, Houston USA), Francis Gannon (Baylor College of Medicine,Houston USA), Srinivas Rangampetta (Indian Institute for Chemical Technology, Hyderabad), Vijaya Mysorekar (M. S. Ramaiah Medical College and Hospital, Bengalore) and **V. Lakshminarayanan (RRI).**

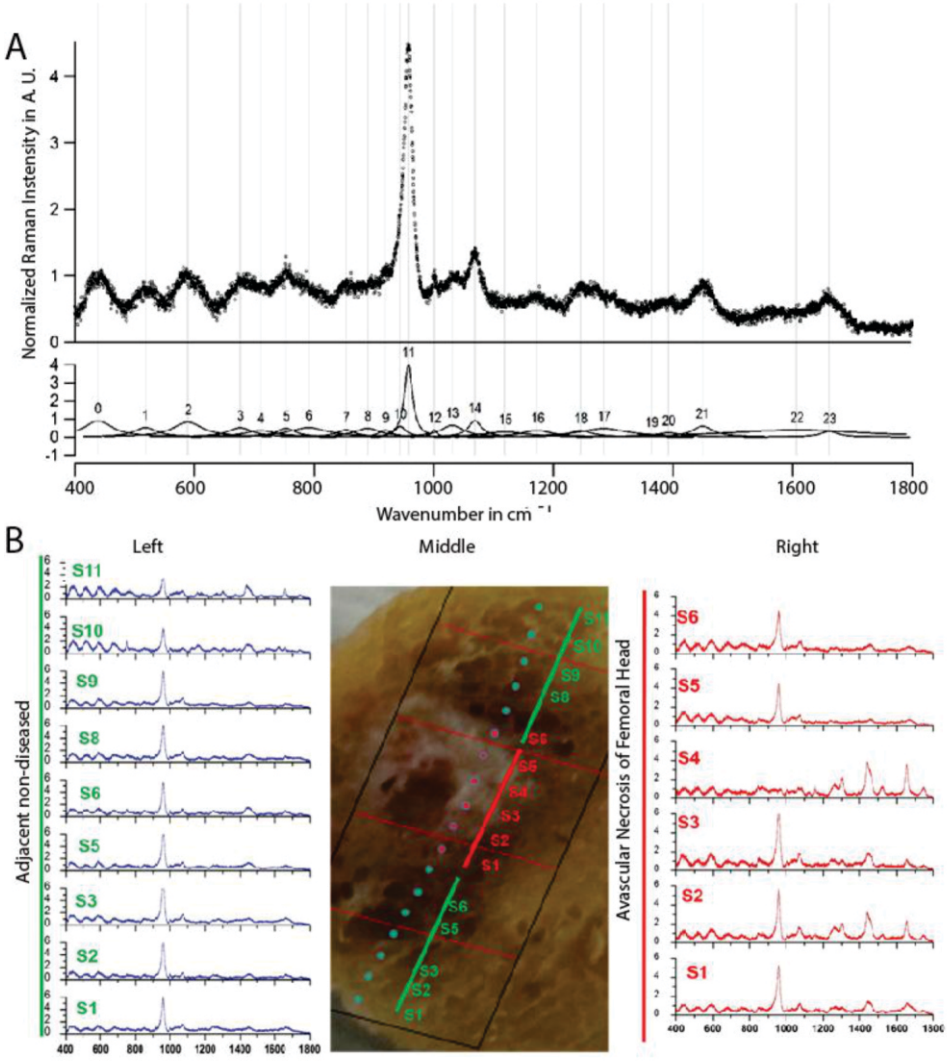


Figure 6. Overview of Raman spectrum obtained in this study. A) Representative Raman spectrum for the femoral bone. X-axis represents the various peaks defined by Wave number and the Y-axis represents the intensity of the peaks in arbitrary units. The inset below in panel A describes the chemical identity of each of the Raman peaks in the spectrum. Supplementary Tables 1 and 2 describe the association between the peak numbers and chemical groups based on reported literature. B) Representative image comparing Raman spectrum from multiple spots in the adjacent non-diseased and AVNFH region in a cross section of AVNFH trabecular bone. Panels markers Left and Right represent the c onsecutive line scans from adjacent non-diseased and AVNFH regions respectively. Panel marked Middle represents the regions within the trabecular cross section that were marked as either adjacent non-diseased (green, spots S1-S6 and S8-S11) or as AVNFH (red, spots S1-S6), respectively.

Avascular necrosis of the femur head (AVNFH) is a debilitating disease, affecting mostly the middle aged population between the age group of 25-50 years. Most of the cases progress to secondary hip arthritis leading to a total hip replacement. The etiology of this disorder is either unclear (and hence termed idiopathic) or could result from the use of alcohol, steroids, smoking as well as pregnancy and trauma. Clinically AVNFH is associated with an impairment of blood supply to the femoral head resulting in bone death and collapse. Epidemiological data suggest an association between mutations in Methyltetrahydrofolate reductase (MTHFR) a key enzyme in homocysteine (HC) metabolism. This is known to result in high levels of HC that is known to induce osteoclast differentiation in macrophages as well as enable inflammatory gene expression in both osteoblasts and osteoclasts. There is however very little information on expression levels of metabolites associated with HC pathway in AVNFH, while association of various biochemical parameters with AVNFH have also not been extensively examined. Furthermore, ultrastructural changes and associated molecular alterations in the AVNFH bone samples have not been well characterized. Using a combination of retrospective analysis of clinical data, mass spectrometry-based metabolite analysis of AVNFH plasma as well as

micro-Raman spectroscopy and Scanning Electron Microscopy-based biophysical measurements of AVNFH bone, for the first time the group has identified key features associated with this disorder. Their results show elevated levels of HC and its associated pathway metabolites, significant alterations in the mineral composition and morphology of the bone as well as key histopathological changes associated with AVNFH bones. Additional studies are warranted to determine the exact role of homocysteine in bringing about these changes associated with onset and progression of AVNFH.

Gautam V. Soni's research focuses on stuying various biophysical phenomena in complex biological systems but at the nanoscale.

Understanding the physical mechanisms of biological structures and machines, at the molecular and cellular scale is paramount to understand developmental biology and diseases. With this larger goal in mind, the Soni group's research targets are primarily guided by the intriguing synergy of structures in biological systems and the related functional dynamics. They use, as well as develop, novel nano-technological tools to decipher biophysical principles that govern self-assembly of proteins and DNA-protein complexes such as chromatin fibers.

Changes in chromatin structure (The DNA double-helix is condensed and packed within the nucleus of a eukaryotic cell with the help of nuclear proteins called histones. The resultant packaged DNA is called chromatin) are a key element in epigenetic gene control. Activation and/or transcriptional-silencing of genes via condensation-decondensation of chromatin is the way researchers go about achieving gene control. Defects in how chromatin is locally condensed are relevant to physiological and pathological processes. However, the molecular mechanisms that establish and maintain functionally distinct chromatin compaction states are poorly understood.

Soni's preferred method of attacking the problem lies in the use of a plethora of single molecule nanoscience tools. Specifically, they plan to use combinations of nanopore biosensing and optical tweezer based force spectroscopy to understand –

1) Kinetics and structural role of nucleosome-nucleosome (basic unit of packaged DNA in eukaryotic cells consisting of a DNA segment spooled around eight histone cores) interactions in forming folded chromatin and

2) Role of architectural proteins (histone proteins) in chromatin compaction for transcriptional inactivation.

In the last year, the group has progressed towards single molecule detection by devising variety of novel nanodevices and through fluorescent microscopy methods -

(i) Starting with **borosilicate glass nanopores** Soni and his collaborator J. Bafna (former VSP student, RRI) has successfully exhibited fabrication, characterization and single molecule detection using these nanodevices.

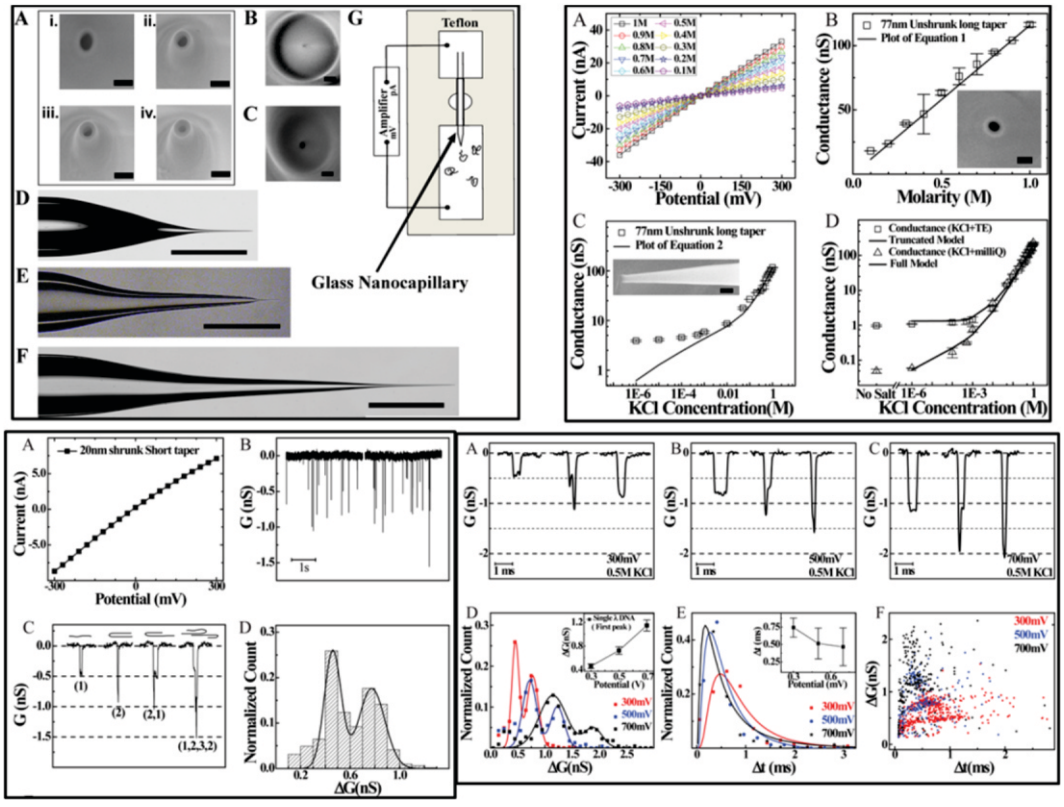


Figure 1: Top Left shows fabrication of borosilicate nanopores down to 6 nm (scale bar is 50nm). Top right shows ion conduction characterization of these nanodevices. Bottom left shows detection of single DNA molecules translocating through a 20nm pore. Bottom right shows voltage dependence of these devices in the context of single DNA detection. [Image courtesy: **Fabrication of Low Noise Borosilicate Glass Nanopores for Single Molecule Sensing,** J.Bafna & G.V. Soni, (under review) PLOS ONE (2016)]

(ii) The next step for Soni has been the **development of a newer version of these nanopore devices using Quartz** over borosilicate glass. These devices are not only much lower in noise but also much more reproducible and biocompatible. Fig. 2 shows preliminary data on these new devices.

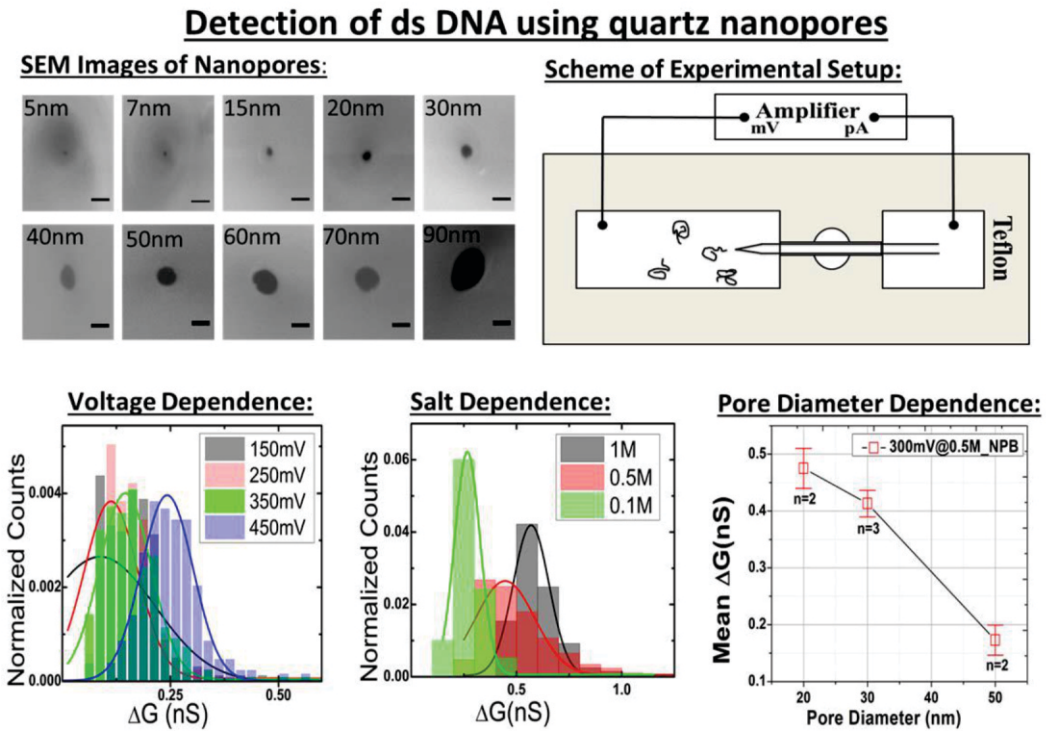


Figure-2: Top row shows fabrication of Quartz nanopores from 5 - 90 nm (scale bar is 50nm) and the experimental setup used to detect DNA. Bottom row shows voltage, salt and pore diameter characterization of DNA detection using these Quartz devices. [J. Bafna & G.V. Soni, in preparation]

(iii) Collaborating with Cees Dekker (Kavli Institute of NanoScience, TU Delft) and Don Cleveland (UC San Diego, USA), Soni has measured the molecular volume of CENP-A nucleosomes. This work has paved way to resolve long standing questions in the field of nucleosome architecture during chromosome segregation in the process of cell division. [**Human centromeric CENP-A-containing chromatin is a homotypic, octameric nucleosome with loosely held DNA termini at all cell cycle points**, N. Arbely, G.V.Soni et.al. (Submitted)].

(iv) Another experiment initiated by the group is for measurement of size, charge and elasticity of biological cells. Biological cells have been known to change their size and elastic properties as a function of progression of cell state, specifically in the case of disease progression. Soni and his collaborators are developing a new micro-capillary based assay to measure physical properties of biological cells. As a first step towards this, they are working towards measuring charge, size and, in future, elastic properties of micro-particles traversing through a micropore device. A data of note here would be the size of typical biological cells. A typical prokaryotic cell (e.g. bacterial cells) is ~ μm in size while a eukaryotic cell (e.g. all animal and plant cells) are ~ tens of μm in size. Fig. 3 below shows preliminary data obtained in this experiment.

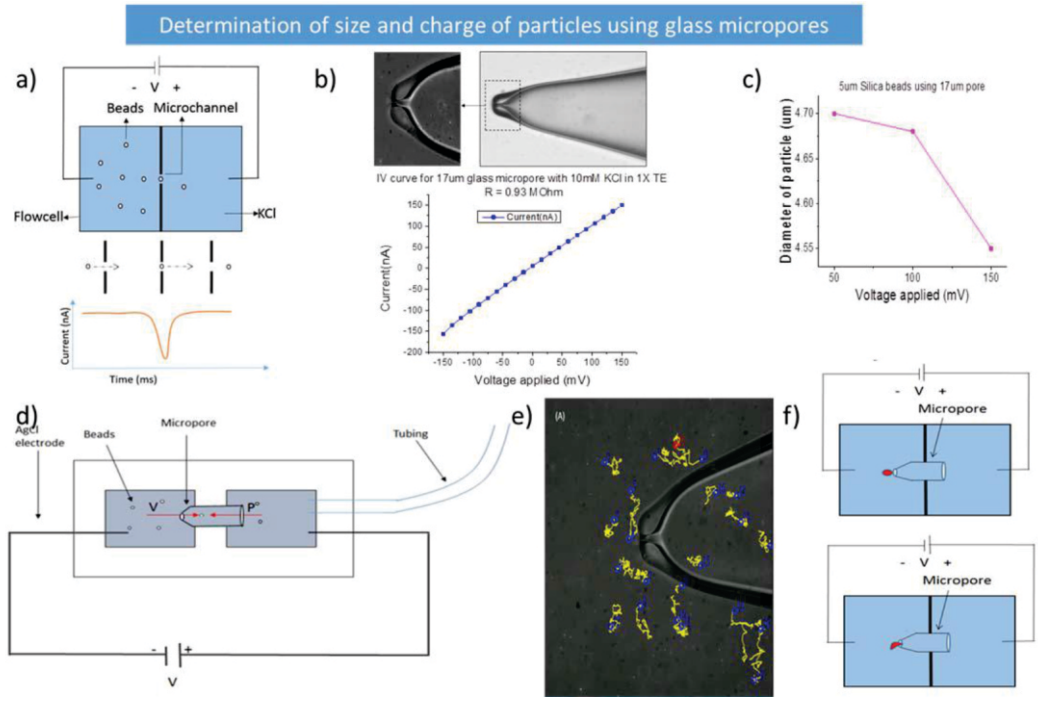


Figure-3: Figures a) Resistive pulse technique to detect particles, b) Micropore of size 17um fabricated in our lab and IV characteristics, d) Measurement of size of known 5um Silica beads, d) Setup for Millikan Oil drop-like experiment for charge measurement by balancing forces on particle due to pressure and voltage, e) Demonstration of pressure control on fluid flow through micropore, f) Experimental proposal to measure stiffness of living cells.

(v) During the previous year, Soni has also started working on genome editing properties of the CRISPR-Cas9 system. He will be studying the efficacy of genome editing by Cas9 system in the presence of nucleosomes on DNA.

(vi) Considering the nature of Soni's research problems and his scientific methods of preference, he has also been engaged in setting up in-house a soft-lithography facility for microfluidics experiments. That apart, Soni and his group have used the following facilities at RRI to conduct his research in the past year - (a) RRI mechanical workshop to construct a Faraday boxes and flow cell for microfluidics facility. (b) RRI SEM facility to characterize and image nano-capillaries. (c) RRI AFM facility extensively to characterize our DNA samples.

D. VIJAYARAGHAVAN's area of professional research interest lies in studying self-assembly of single-walled carbon nanotubes in surfactant and polymer solutions.

During the year gone by Vijayaraghavan has studied **self-assembled CNT-polymer hybrids in single-walled carbon nanotubes dispersed aqueous triblock copolymer solutions.** Block copolymers in solution are used to disperse and induce assembly of nanostructures including nanoparticles, nanorods and carbon nanotubes into mesostructures. Therefore, it is essential to understand the interaction between the polymers and nanostructures in the combined polymers-nanostructures-solvent systems. Understanding the self-assembly of polymers in the presence of these nanostructures will aid future designing of desired self-assembled polymer structures. The amphiphilic block copolymers poly(ethylene oxide)-poly (propylene oxide)-poly (ethylene oxide) PEO_y PPO_xPEO_y or Pluronic block copolymers self-assemble in water into micelles consisting of hydrophobic PPO core and solvated PEO corona. Though the dispersion of colloidal particles like carbon black in polymer solution does not affect the self-assembly of polymer molecules and the structure of the formed micelles, the dispersion of carbon nanotubes in polymer solutions is found to modify the temperature, enthalpy and dynamic behavior of polymer self-assembly. Florent et al. reported EPR studies on a Polymer-CNT-water system which revealed that the PO segments of the

polymer molecules are adsorbed on CNTs and form CNT–ploymer hybrids. The small diameter of the single-walled carbon nanotubes (SWCNT) enables the formation of polymer molecule aggregates that is similar to the native micelle, with the SWCNT located at the core of the micelle. Below critical micelle temperature (CMT), only unimers are adsorbed on the CNTs. However, above CMT, both the unimers and micelles are adsorbed on the CNTs.

In order to probe these systems further, Vijayaraghavan has carried out scanning electron microscopy (SEM), differential scanning calorimetry (DSC), small angle X-ray scattering (SAXS), electrical conductivity and ^{1}H NMR studies as a function of temperature on SWCNTs dispersed aqueous triblock copolymer (P123) solutions. The single-walled carbon nanotubes in this system aggregate to form bundles and the bundles aggregate to form net-like structures. Depending on the temperature and phases of the polymer, this system exhibits three different self-assembled CNT-polymer hybrids. We find CNT-unimer hybrid at low temperatures, CNT-micelle hybrid at intermediate temperatures wherein the polymer micelles are adsorbed in the pores of the CNT nets and another CNT-micelle hybrid at high temperatures where in the polymer micelles are adsorbed on the surface of the CNT bundles. Our DSC thermogram showed two peaks related to these structural changes in the CNT-polymer hybrids. Temperature dependence of the ^{1}H chemical shifts of the molecular groups of the polymer and the AC electrical conductivity of the composite also showed discontinuous changes at the temperatures at which the CNT-polymer hybrid's structural changes are seen. Interestingly, for a higher CNT concentration (0.5wt.%) in the system, the polymer micelles adsorbed on the CNTs aggregate to form flower-like and cube-like morphologies at the intermediate and at high temperatures respectively.

{All images reproduced below courtesy J Mol. Liq.; from **Aggregates of single-walled carbon nanotube bundles in a surfactant solution**, D. Vijayaraghavan, Journal of Molecular Liquids 2015, 209, 440}.

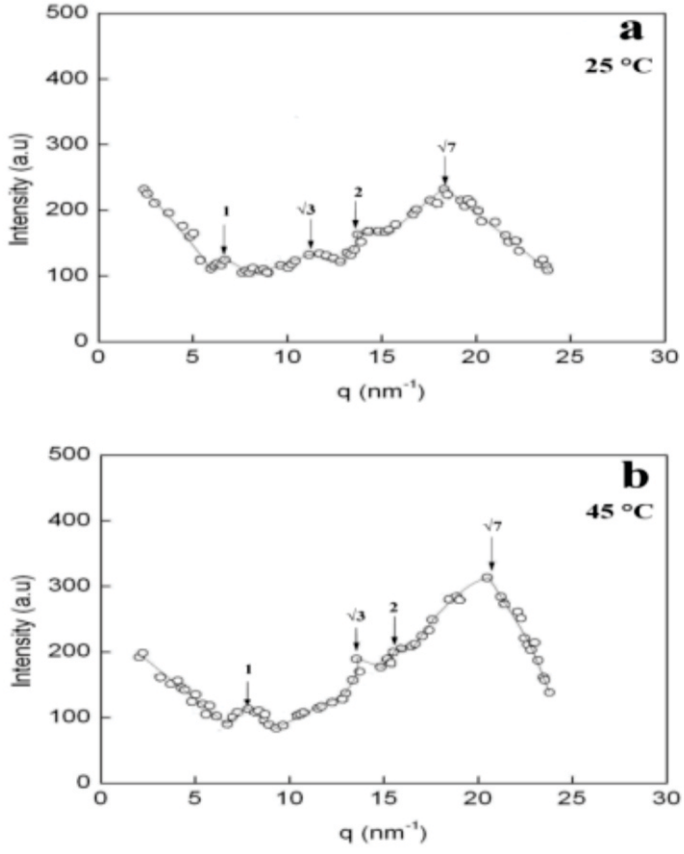


Figure 1: SAXS pattern of 0.25 wt. % SWCNTs dispersed aqueous (D_2O) solution containing 2.5 wt. % P123 at two different temperatures (25 and 45^{o}C). The SAXS pattern exhibits peaks in the ratio 1: √3:2:√7 indicating a 2D hexagonal structure similar to the SAXS pattern reported for SWCNT bundles.

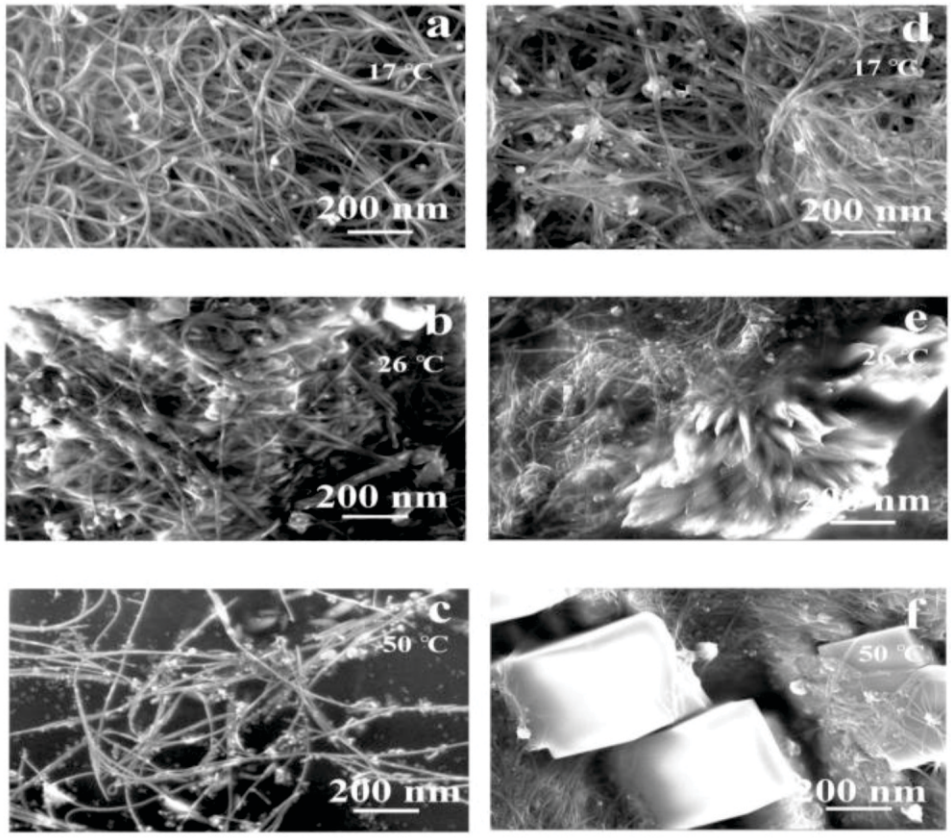


Figure 2: SEM images of SWCNTs dispersed aqueous (D_2O) solution containing 2.5 wt. % P123 as a function of temperature for 0.25 wt. % CNTs (a-c) and 0.5 wt.% CNTs (d-f). At low temperatures (below CMT) the polymer unimers are adsorbed in the pores of the net-like structures of the CNT bundles (Figs. a and d). At intermediate temperatures (above CMT), the polymer micelles are adsorbed in the pores of the CNT structures (Figs. b and e). At higher temperatures, the micelles are adsorbed on the surface of the CNT bundles (Figs. c and f). For a higher CNT concentration (0.5 wt.%) in the system, the polymer micelles adsorbed on the CNTs aggregate to form flower-like and cube-like morphologies at the intermediate and at high temperatures respectively (Figs. e and f). CNT bundle diameter decreases with increasing the concentration of CNTs in the polymer solution or increasing the temperature of the system.

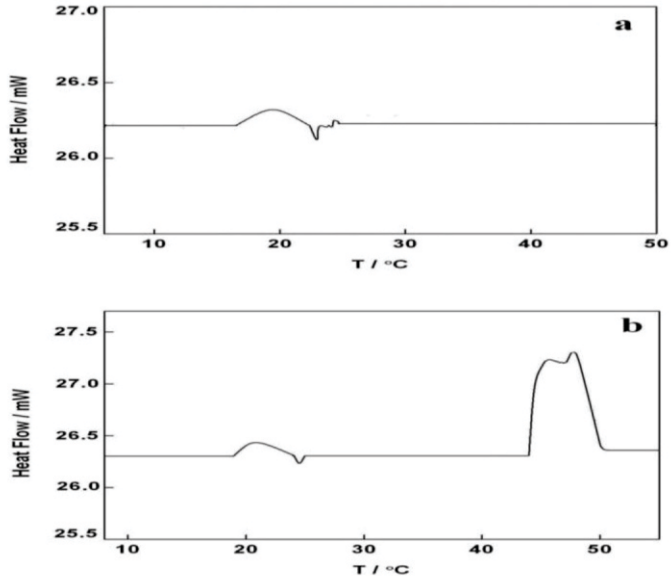


Figure 3a shows the DSC thermogram on heating for the native polymer solution (2.5 wt. % P123 in D_2O). The thermogram exhibits an exothermic peak at 20.6° C. We believe that the peak is related to the unimer to micellar phase transition of the polymer. Fig. 3b shows the DSC thermogram on heating for 0.25 wt. % SWCNTs dispersed polymer solution. The thermogram exhibits two exothermic peaks one at 20.7°C and another at 47.5°C. We believe that the peaks are related to the structural changes in the CNT-polymer hybrids in the system. The low temperature peak is related to the transition of the CNT-unimer hybrid to CNT-micelle hybrid wherein the micelles are adsorbed in the pores of the CNT net-like structures and the high temperature peak is related to the transition of the CNT-micelle hybrid to another CNT-micelle hybrid wherein the micelles adsorbed on the surface of the CNT bundles as seen in our SEM images (Fig. 2a – 2c).

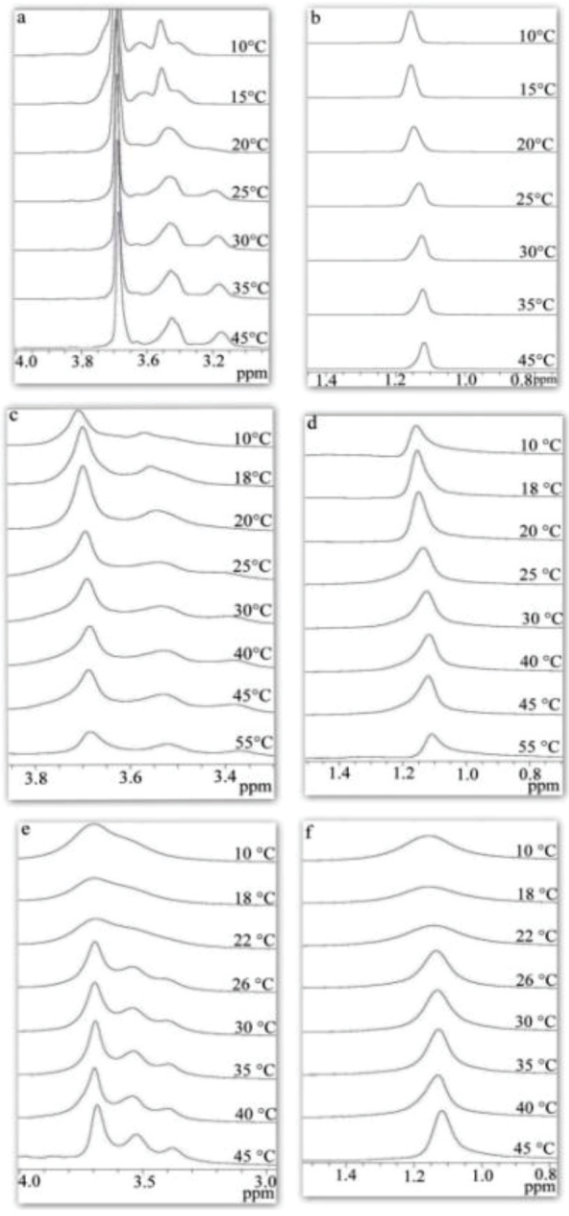


Figure 4. ^{1}H NMR spectra for SWCNTs dispersed aqueous (D_2O) solution containing 2.5 wt.% P123 as a function of temperature for 0 wt.% (a and b) , 0.25 wt. % (c and d) and 0.5 wt.% CNTs (e-f) . The spectra corresponding to the PO-CH_3 groups of the polymer are shown in the Figs. b,d and f. The spectra corresponding to the EO-CH_2 and PO-CH_2 groups of the polymer are shown in Figs. a, e and f.

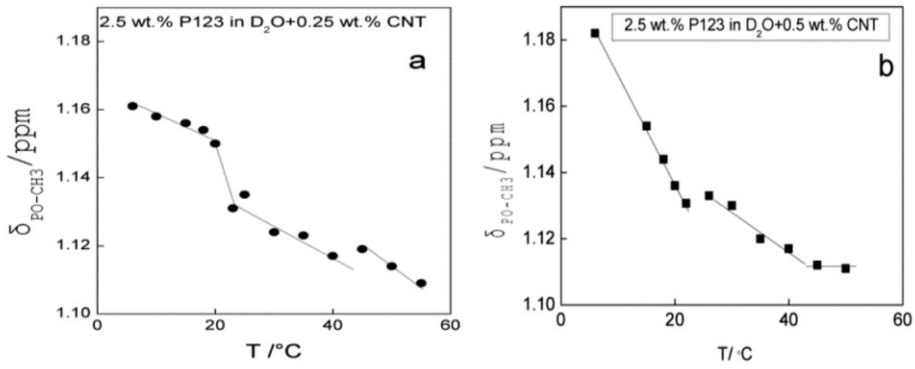


Fig. 5. The temperature dependent chemical shifts of the PO-CH_3 groups of the polymer in the case of a) 0.25 wt.% CNTs and b) 0.5 wt.% CNTs dispersed in the aqueous solution containing 2.5wt.% P123. Discontinuous changes in the chemical shifts are seen at the temperatures at which the structural changes of the CNT-polymer hybrid are observed.

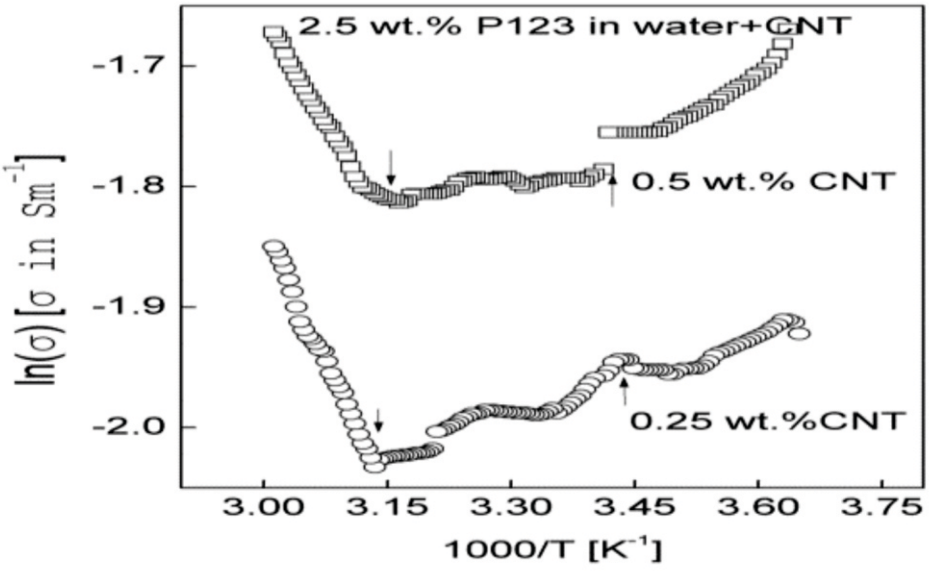


Fig. 6. Arrhenius plots for AC electrical conductivity (σ) for 0.25 wt. % and 0.5 wt.% SWCNTs dispersed in aqueous triblock copolymer (P123) solution. The plots show discontinuous changes at the temperatures at which the structural changes of the CNT-polymer hybrid is observed.

Anuradha Bhattacharya (Post-doctoral Fellow, RRI) has current professional research interestss in single molecular force spectroscopy of soft polymers and cytoskeletal proteins and investigation of mechanical strength of such complexes by optical tweezer and atomic force microscopy.

The cytoskeletal components of the cell provide it with structural and functional support. Thesecytoskeletal elements consist of microtubules, intermediate filaments and microfilaments. In current literature cytoskeletal filament components have been attributed with some functional significance in the cell. Among these filaments the most extensively studied are the actin filaments. Bhattacharya's goal in collaboration with **Pramod Pullarkat (RRI)** was to understand the mechanobiological aspect of actin in tether formation in chick neurons. The tether was pulled by attaching a bead held in an optical trap on the cell surface and then pulling the bead by moving the piezo. Bhattacharya has plated cell cultures of chick neurons for the study. She has also worked on the calibration and the tether pulling from the chick neurons.

Currently she is studying the biomechanical properties of the beaded filament network in the eye lens in collaboration with **G.V. Soni (RRI)**. The beaded filament network as the name suggests has 10 to 15 nm diameter filaments with beads interspersed between the filaments. Knocking out these filaments in the eye lens of mice has been shown to cause cataract. Hence elucidating the role of these filaments in the human eye lens is an important indicator of cause of cataract which affects millions of people around the world.

The beaded filament is composed of the BSFP1, BSFP2 and crystallin proteins. These proteins can be dialyzed to assemble as filaments with beaded morphology in-vitro. Cataract is caused by scattering of light by the aqueous humour which fills the voids in the eye lens when close packing arrangement of the fiber cells in the eye lens in disturbed. The second cause of this disease is the agglomeration of lens proteins in the eye lens which is normally prevented by alpha crystallin present.

Gold nanoparticles are found to adsorb on crystallins when they are of an optimum size. The crystallin proteins are also associated with the beaded regions of the beaded filaments. Hence adsorption of gold nanoparticles on the beaded portion of the filaments will impart the cell mechanical stability preventing void formation and scattering of light. Also gold nanoparticles with optimized size and concentration are found to assist the chaperone activity of crystallin preventing agglomeration of gamma crystallins in the eye lens.

The first stage of this project would be to measure the mechanical stiffness of the eye lens with and without gold nanoparticles. At present Bhattacharya is studying the mechanical stiffness of soft PDMS polymer with atomic force microscope. She has synthesized PDMS polymer of different elastomer to curing agent ratios and is using the force distance curve in the contact mode of AFM. This is a first step calibration of the instrument before being used to measure the eye lens stiffness. The principle of the force distance curve of afm is that a nanometer radius of curvature tip is employed to indent the PDMS surface. The deflection of the cantilever is directly proportional to the force on the sample. From the force distance curve the adhesion, mechanical constants like the Hamaker constants can be determined. The data obtained is further analyzed and fitted with existed models to find the elasticity of the sample.

Nupur Biswas (Post-doctoral Fellow, RRI)

has research interests currently focused on the resistive pulse technique, thus far largely used to detect biological macromolecules at the single molecule level, and its possible application in 1) distinguishing two emulsified immiscible liquids - in particular - oil in water or oil-like pollutants in water and 2) vesicle (spheroidal structures bounded by a lipid bilayer) translocation through a micro/nanopore.

Resistive pulse technique, originally invented for counting number of blood cells, has evolved a lot over the years. In the resistive pulse technique, salt ions are allowed to pass uninterruptedly through a micrometer or nanometer sized pore under a constant bias voltage (Fig. 1). Consequently, one gets a constant current. Some molecules/particles are added on one side of the pore. These molecules/particles are then forced to pass through the pore by applying pressure or by bias voltage. While passing through the pore, the molecule or particle actually blocks the path of ions and hence induces a drop in current. The magnitude of this current drop and duration of the drop carry information about the particle. Frequency of this current drop 'events' would naturally indicate particle concentration.

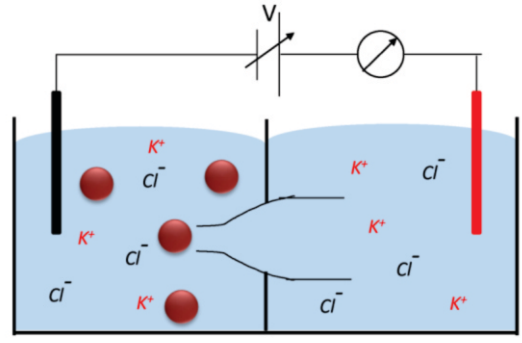


Fig. 1: Schematic of translocation experiment

The emphasis though has shifted now to detection of several biologically significant macromolecules and their complexes at single molecule level and possibilities for DNA sequencing are being explored. It is also successfully being used for detection of several other entities like various micro and nanoparticles, liposomes, virus – all of which are either solid or soft matter. In this context Biswas wants to investigate whether by applying voltage she can distinguish two immiscible liquids and also vesicle translocation.

Emulsion is colloidal state of two immiscible liquids. The most popular example of emulsion is milk. However, oil in water is also another important emulsion, which often appears as polluted water. **Biswas'** experiment would help in **quantitative measurement of the presence of oil and oil-like pollutants in water.** For this experiment, she has chosen a very common organic liquid xylene, which does not dissolve in water and can form an emulsion in water. She has then prepared emulsion of xylene droplets in aqueous buffer.

In the resistive pulse experiment, the particle is liquid – it is in the form of a droplet. Fig. 2a below shows optical microscope image of xylene droplets in aqueous buffer. The micropore was prepared from glass capillary having pore diameter 22 micron (Fig. 2b). Fig. 3 shows the current (I) – voltage (V) relation of the pore in presence of 10mM KCl in 1x TE buffer. The graph appears linear and its slope provides a pore resistance 4.1 MegaOhm. The preliminary data (Fig. 4a) shows the presence of xylene droplets can be detected successfully while they pass through a micropore resulting in a drop of current. Fig. 4b illustrates the shape of one particular drop indicating passage of one droplet. Fig. 4c shows the distribution of change in conductance.

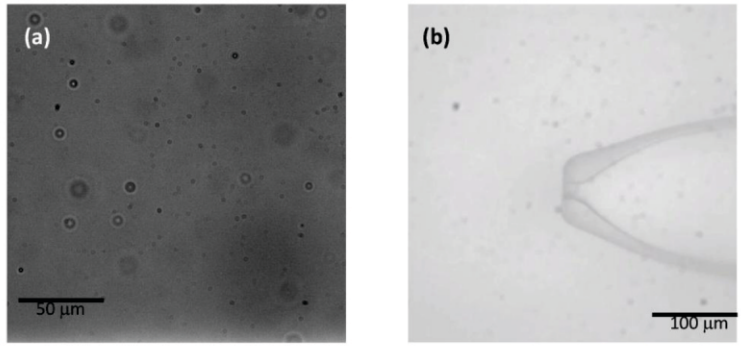


Fig. 2: Optical microscope image of (a) xylene droplets in aqueous buffer and (b) glass micropore.

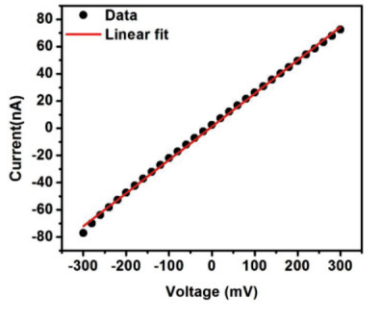


Fig. 3 : Current (I) – voltage (V) relation of the pore in presence of 10mM KCl in 1x TE buffer.

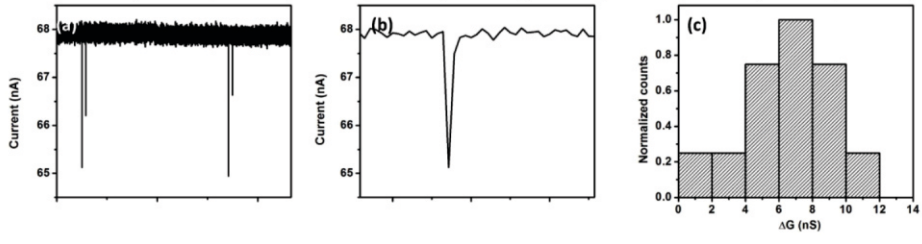


Fig. 4 : (a) Change in current as droplets pass. (b) Current drop for a single event. (c) Distribution of change in conductance.

The conclusion is that resistive pulse method can be applied for detection of the presence of a second liquid in one and for quantifying the presence of the impurity such as its, size and surface charge of the droplets. These experiments are presently underway.

The major component of cell membrane is lipid bilayer. Lipid molecules are a special type of molecules having a long hydrophobic chain (tail) and a relatively small hydrophilic part (head). Vesicles are spheroidal structures enveloped by a lipid bilayer. Hence, they can be thought of as a simple model of cell. Vesicles can be synthesized in various ways depending on the required size. Vesicles of diameter 20 – 200 nm are called Small Unilamellar Vesicles (SUV) and are prepared by extrusion method. On the other hand, vesicles of diameter more than 1 micron are called Giant Unilamellar Vesicles (GUV) and are prepared by electroformation method.

In this project, **Biswas** is interested in **vesicle translocation through micro/nanopores.** The experiment aims to explore the effect of pressure induced translocation on vesicle structure. They also want to use vesicles as carrier under different pH condition.

The group has successfully synthesized both SUVs and GUVs. Fig. 5a below shows a confocal microscope image of GUVs formed by DPPC lipids. They have used Bodipy-C12 dye and 488 nm laser for excitation. Fig. 5b shows the size distribution of GUVs. The group is now working on successful translocation of SUVs as well as GUVs.

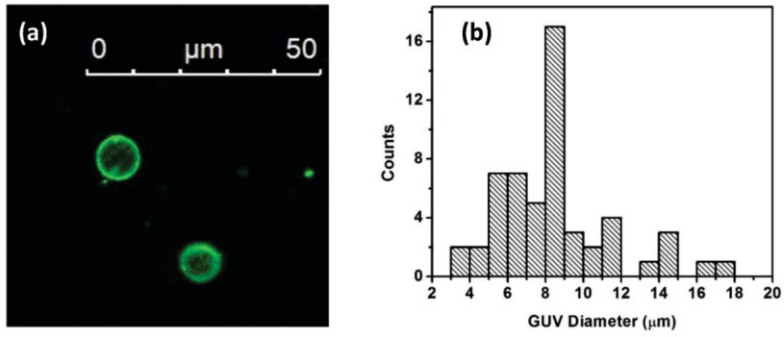


Fig. 5: (a) Confocal image of GUVs made from DPPC lipid and (b) their size distribution.

Paramesh Gadige (Post-doctoral Fellow, RRI) has as hisarea of research interest dynamics in glass-forming liquids, glasses and complex fluids. Over the year gone by he has explored the following problems:

(i) **Rheological hysteresis in aging Laponite colloidal suspensions** in collaboration with **Ranjini Bandyopadhyay (RRI).** Nonlinear rheology has now found applications in studies of the complex dynamical behavior of soft glasses. In this experiment Gadige has carried out nonlinear rheological studies as function of aging time for Laponite colloidal suspensions by recording rheological hysteresis loops. Shear stress vs shear rate is monitored by sweeping up and down the shear rate over a finite time window. The up and down sweeps of the shear rate do not superimpose and result in rheological hysteresis loops. The area under the curve gives the energy dissipated due to the structural breakdown of the colloidal suspensions. It is found that the hysteresis area increased with increasing aging time for the laponite suspensions and is found to depend on the finite step size or sweep rate of the shear rate. This suggests the strengthening of the structure with aging and breaking the structure or shear melting depends on sweep rate or step size of the shear rate. Further data analyses and investigations are in progress.

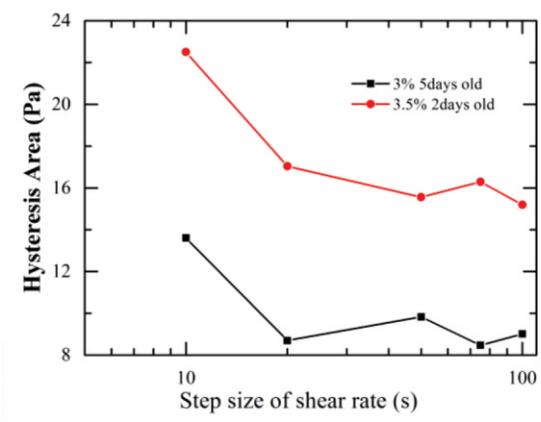


Fig.1. Shear rate step size dependent hysteresis area for aged Laponite suspensions for 3% and 3.5 % (w/v)

(ii) Zeta potential and dielectric studies on volume phase transition of poly (N-isopropylacrylamide) (PNIPAM)

suspensions, in collaboration withYogesh M Joshi (IIT Kanpur) and **Ranjini Bandyopadhyay (RRI).**Stability of the colloidal suspensions is very important in the study of their physical properties as the inter-particle electrostatic repulsions and the density difference between particles and solvent play a major role in stabilizing the colloidal particles. In order to understand inter-particle electrostatic interactions of thermosensitive poly (N-isopropylacrylamide) (PNIPAM) suspensions z-potential and conductivity of the PNIPAM suspensions are measured using electroacoustic probe and four-point conductivity meter respectively. PNIPAM particles were found to possess negative z-potential at room temperature whereas significant change and sign reversal of the z-potential is observed above the volume phase transition temperature.

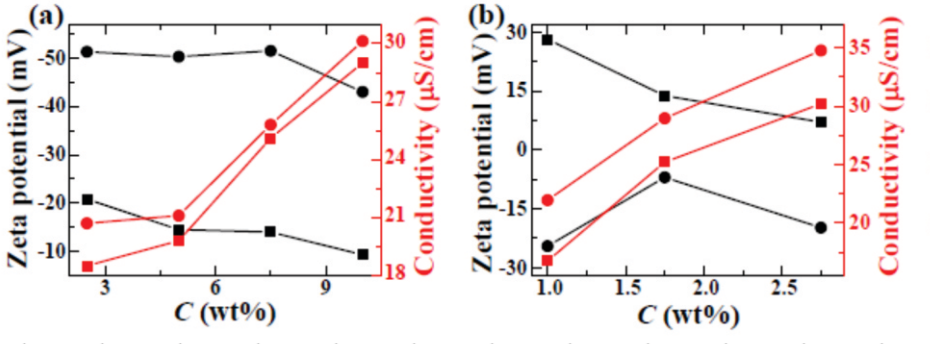


Fig.2. Zeta potential and conductivity of PNIPAM suspensions for different concentrations above and below the volume-phase transition

Volume phase transition of these thermosensitive PNIPAM suspensions are also studied using dielectric measurements. Capacitance and impedance of thermosensitive PNIPAM particle suspensions are monitored in the temperature range 20-45^{o}C at 1 kHz frequency. This dielectric study detected the volume phase transition of thermosensitive PNIPAM hydrogels around 32-34^{o}C. Analysis showed that the imaginary part of impedance is more sensitive to the phase transition than the dielectric constant.

(iii) **Electric modulus studies in aging Laponite suspensions,** with collaborators Yogesh M Joshi and **Ranjini Bandyopadhyay (RRI).** Dilelectric measurement experiments were continued by Gadige on soft colloidal glass formation of aging Laponite suspensions (3.5 % (w/v)). Capacitance measurements are carried out at 1 kHz for Laponite as aging progresses. It is found that the real part of electric modulus (M') increased with aging whereas the imaginary part of electric modulus (M") decreased. The crossover of the M' and M" is observed above the glass transition (~7.5h) during the aging similar to the crossover of storage modulus (G') and viscous modulus (G") seen in rheological studies.

(iv) **Dynamical heterogeneities in aging Laponite suspensions** is another research work donein collaboration with **Debasish Saha (PhD student, RRI), Sanjay Kumar Behera (PhD student, RRI)** and **Ranjini Bandyopadhyay** (RRI).

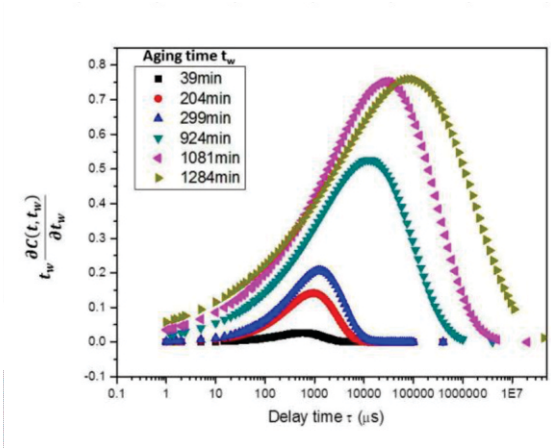


Figure 3: Growth of peak height of three-point correlation function as Laponite suspension ages.

Pramod Tadapatri's areas of professional research interests are studies of electro-optic, dielectric and optical properties of liquid crystals, and optical and dielectric studies of polyelectrolytes.

During the period 2015-16, Tadapatri has worked on the **unusual phase sequence in a bent-core liquid crystal.** Not only do bent-core liquid crystals exhibit different phases as compared to those seen in rod-like systems, but they also exhibit unusual phase sequence involving different phase structures. The bent-core molecules are strongly polar and biaxial in shape and thus strongly deviate from cylindrical symmetry. Some of the interesting phases are polar smectic phase, orthogonal smectic phase, reversed columnar phase and dark conglomerate phases. There are many reports on the interplay of phases having one-dimensional and two-dimensional lattices. These phases with different lattices show different polarization characteristics such as ferroelectric or antiferroelectric. Further, the different mechanisms involving phase structures and ordering affect these polarization characteristics making bent-core systems very complex and challenging to study.

An achiral seven-ring bent core compound derived from 5-methoxyisophthalic acid (SRC12) has been studied during the period of this report. It shows a transition from the antiferroelectric phase to a ferroelectric phase determined by switching characteristics. In a temperature range below these phases Tadapatri has observed an additional phase transition. The transitions have been detected in dielectric studies. Calorimetry studies have also confirmed the phase transitions. More detailed X-ray diffraction studies are now underway to correctly determine the nature of the phases.

THEORETICAL PHYSICS

Overview

The major areas of research pursued by the Theoretical Physics (TP) group are statistical physics, including non-equilibrium statistical physics, biophysics, soft condensed matter and quantum many-body physics, quantum gravity, general relativity and foundations of quantum mechanics. The TP group, by the very nature of its work, often interfaces and collaborates with experimental groups within RRI such as the Light and Matter Physics group, especially in the areas of foundational questions in quantum physics, and the Soft Condensed Matter group, in areas such as biophysics and non-equilibrium statistical physics. There are also collaborations with experimentalists working in these areas outside the institute.

Current Research Interests

Statistical Physics

The TP group is currently engaged in research on the equilibrium and dynamical properties of polymers. A problem that the group is working on at the moment is that of ring-closure probability of semi-flexible polymers using the Worm-like Chain model or the WLC model. The WLC model consists of a completely flexible isotropic rod as the connector between two carbon atoms in the polymer chain. The semi-analytical results obtained so far show a power law (a relation between two variables such that a change in one results in a proportionate change in the other independent of initial values of either variable) decay in the ring-closure probability with the contour length (the maximal physically possible extension) of the polymer in question over a range of length scales. The above study can have implications for biophysical studies of DNA and actin filaments.

Non-Equilibrium Statistical Physics

A theoretical understanding of some basic questions in standard non-equilibrium statistical physics is also one of the aims of the TP group. To this end research is being carried out by the TP group on large deviations for Markov processes (random statistical processes whose current state is unaffected by memory or rather 'memory-less' systems) with resetting (restarting or initialization), random walk with random resetting to the maximum position, exact probability distribution for two-tag displacement in a constrained single-file motion of point particles where the point particles have hard-core repulsive inter particle interaction that prevents particle crossings, and fluctuation theorem for entropy production of a partial system in the weak coupling limit. The last work shows that when one small system is in contact with a heat bath is weakly coupled to a similar one; it becomes possible to infer the presence of such weak coupling by observing the violation of the steady state fluctuation theorem for the partial entropy production of the observed system.

Biological Physics

Members from the Soft Condensed Matter and Theoretical Physics groups are together involved in the work being done on various topics in the field of biophysics but which concentrate primarily on understanding the mechanics of living systems (cells, tissues etc.) at different scales and how that helps in organizing molecules and arranging cells etc. with broader implications for homeostatic control. These problems include studies of vesicle formation and their transport in cells, mitochondrial distribution dynamics, DNA stretching and twisting, molecular transport through the secretory pathway in cells, the active composite cell surface, active tissue mechanics, biogenesis of organelles using non-equilibrium physics models and active mechanics of membranes, polymers, fluids, solids, semisolids etc. Cell mechanics from the point of view of information processing and computation embodies another very interesting biological problem with the potential to overthrow many established ideas behind the whys and hows of cell mechanics. Research in biophysics at RRI involves active collaborations not only within the Institute but also with the National Centre for Biological Sciences, Bangalore, TCIS-TIFR, Hyderabad, IIT Madras, and several institutes abroad.

Quantum Gravity

The TP group at RRI carries out research on quantum gravity from two distinct viewpoints, Loop Quantum Gravity (LQG) and Causal Set Theory (CST).

LQG is a method where standard Hamiltonian ways of quantization are applied to the classical gravitational field without resorting to perturbation theory. The consequent absence of a spatial geometry in LQG has been addressed through some new ideas and tools by the TP group, while the absence of a background time and an overall recovery of the space-time continuum in the classical limit are the two issues being looked into currently. Entanglement entropy, coherent states and their effect on gravity and quantum dynamics and long-distance correlations in a polymer-parameterized field theory constitute the efforts by the TP group in this area during the last year. The work evidently employs statistical physics concepts such as entropy and polymer theory.

In the CST approach to quantum gravity, on the other hand, one replaces continuum space-time by a discrete substructure, which is a locally finite, partially ordered set, the Causal Set. While the partial order represents the underlying causal structure of a causal Lorentzian space-time, the local finiteness encodes the hypothesis of a covariant discrete cut-off. In the CST approach the continuum arises as an approximation, rather than as a limit since the cut-off is a physical input rather than a mathematical convenience as in other discrete approaches. At RRI, a broad range of directions in causal set theory has been pursued. These include a close examination of causal set kinematics in which continuum quantities like topology, dimension, curvature and geometry are reconstructed from purely order theoretic considerations. There has also been active work on quantum dynamics using numerical MCMC methods as well as the quantum measure approach. In both cases, the construction of quantum observables rests on previous work on causal set kinematics. Most recently there has been work at RRI on the construction of a discrete propagator in curved space-time by using a local Green's function in 2 and 4 space-time dimensions assigning probabilities to 'hopping' and 'stopping'. During the past year, research has been done at RRI on the large N limit in 2D causal set quantum gravity. This work had earlier shown that 2D causal set quantum gravity shows a phase transition from a continuum phase to a crystalline non-continuum phase that affects the Hartle Hawking ground state (Hartle Hawking ground state is the ground state for the Hartle Hawking wave function for CST).

Another line of investigation motivated by causal sets and quantum cosmology considerations is the quantum measure approach to quantum foundations. Here, one places quantum theory in parallel with stochastic physics with its attendant interpretational generalizations. Work is on at RRI to understand how this framework can be used to obtain covariant observables in quantum gravity. The statistical physics counter part used in the work consists of percolation (trickling of particles or particle-properties through an intervening medium which in the process broadly performs a 'filtration').

Foundational Questions in Quantum Mechanics, Quantum Measurements, and Quantum Equivalents of Classical Systems

The dynamics of quantum particle in a box with moving walls and the existence of an associated non-trivial Berry phase (Berry phase or geometric phase is the instantaneous phase or state of motion that the particle picks up upon undergoing a cyclic motion without any heat exchange resulting from the geometrical properties of the system being studied) is one of the foundational questions in Quantum Mechanics that the TP group in RRI has been working on. The result shows that specific boundary conditions need to be maintained in order to preserve unitarity, or in other words to ensure that the sum of all probabilities associated with the motion of the particle adds up to unity.

During the period 2015-2016, the TP group at RRI has arrived at an extremely important result with far-reaching consequences in the process of measurement in quantum systems. In an analytical study treating the spin of a silver atom as a quantum system in the context of the Stern-Gerlach experiment, the TP group at RRI has proposed the concept of a coarse quantum measurement. It appears that quantum measurements are limited in their resolution by bounded resources, which results in a non-unitary evolution of the system in question, not governable by the Schrodinger equation. It is proposed that the coarseness of the detection process is what renders a quantum system non-unitary. This work was begun in 2014-15 and is now completed.

This year, the TP group has also begun working on diffusion at low temperatures where a quantum version of the law of diffusion based on the fluctuation dissipation theorem is being drafted.

General Relativity

Simple Euclidean methods can successfully reproduce entropy and temperature of black holes derived by completely different methods. Motivated by this, the TP group has used a rotated time direction on a standard Wick rotation (Wick rotation is a method of solving a mathematical problem in Minkowski space or rather in the fabric of space and time by employing a simple transformation of an imaginary number variable to a real number variable on the solution of the Euclidean counterpart of the problem) to arrive at a real Euclidean matrix for describing a rotating black hole.

Dibyendu Roy's research concentrates on theoretical condensed matter physics, statistical mechanics and atomic, molecular & optical physics.

In a paper titled **Strongly interacting photons in one-dimensional continuum** [(arXiv: 1603.06590, http://arxiv.org/abs/1603.06590)] where he has collaborated with C.M. Wilson (University of Waterloo, Canada) and Ofer Firstenberg (Weizmann Institute of Science, Israel), Dibyendu and his collaborators have tried to understand the physics of strongly-interacting photons in one-dimensional systems that are optically bound only in one direction.

The photon-photon scattering in vacuum is extremely weak. However, strong effective interactions between single photons can be realized by employing strong light-matter coupling. These interactions are a fundamental building block for quantum optics. The study focuses on two recent experimental realizations of this theoretical gedanken experiment –

(i) Superconducting qubits coupled to open transmission lines and
(ii) Interacting Rydberg atoms in a cold gas.

The work has several potentially significant technological applications because by bringing many-body physics into the photonic world, it provides important resources for the design and manufacture of quantum photonic devices and for high-precision optical metrology.

Rajeev Singh (Bar-Ilan University, Israel) and Roderich Moessner (Max Planck Institute for the Physics of Complex Systems, Germany) are **Dibyendu**'s collaborators in his second research project this year. Tentatively titled **Logarithmic growth of entanglement in a disordered chain of free fermions with long-range hopping**, the work investigates numerically, the dynamics of entanglement in a chain of spin-less fermions with predetermined long-range hopping and interaction but with random on-site energies. The disordered chain in the absence of interaction hosts delocalized states at the top of the band, which undergo a delocalization-localization transition as and when the magnitude of disorder increases. They find an interesting regime in this non-interacting disordered chain where the long-time entanglement entropy scales as $S(t) \sim \ln t$ and the saturated entanglement entropy scales as $S \sim \ln L$ with L being the system size.

The entanglement dynamics in the non-interacting long-range model shows striking similarities to the random XXZ chain, thus exhibiting a many-body localized (MBL) phase at strong disorder. They further study the interplay of long-range hopping and interaction on the growth of entanglement and MBL transition in this system.

Sanjib Sabhapandit's research interests are in the realm of statistical physics. In the year 2015-16, Sabhapandit has been exploring certain interesting problems that deal with basic questions in non-equilibrium statistical physics.

Of them the first problem is **large deviations for Markov processes with resetting.** His collaborators in this problem are Janusz M. Meylahn (Leiden University, Netherlands, Stellenbosch University, South Africa) and Hugo Touchette (National Institute of Theoretical Physics, South Africa). [Phys. Rev. E 92, 062148 (2015)]

Markov processes restarted or reset at random times to a fixed state or region in space have been actively studied in recent times in connection with random searches, foraging, and population dynamics. In the publication, the authors study the large deviations of time-additive functions or observables of Markov processes with resetting. By deriving a renewal formula linking generating functions with and without resetting, they are able to obtain the rate function of such observables, characterizing the likelihood of their fluctuations in the long-time limit. They have applied this theory to understand the large deviations in the area of the Ornstein-Uhlenbeck process with resetting. Other applications include diffusions, random walks and jump processes with resetting or catastrophes.

With Satya N. Majumdar and Gregory Schehr of LPTMS, Univ Paris-Sud, France, **Sabhapandit** has studied **random walk with random resetting to the maximum position** [Phys. Rev. E 92, 052126 (2015)].

The study involves analyzing a simple random walk model on a one-dimensional lattice, where at each time step the walker resets to the maximum of the already visited positions (to the rightmost visited site) with a probability r, and with probability (1-r) it undergoes symmetric random walk, i.e., it hops to one of its neighboring sites with equal probability (1-r)/2. In presence of a non-zero resetting rate $0 < r \leq 1$, the authors find that both the average maximum and the average position grow ballistically for large n, with a common speed v(r). Moreover, the fluctuations around their respective averages grow diffusively, again with the

same diffusion coefficient D(r). Computing v(r) and D(r) explicitly, they also show that the probability distribution of the difference between the maximum and the location of the walker becomes stationary as $n \to \infty$. However, the approach to this stationary distribution is accompanied by a dynamical phase transition, characterized by a weakly singular large deviation function. They also show that r = 0 is a special 'critical' point, for which the growth laws are different from the $r \to 0$ case and they calculate the exact crossover functions that interpolate between the critical (r = 0) and the off-critical ($r \to 0$) behavior for finite but large n.

Sabhapandit and Abhishek Dhar, ICTS, TIFR, Bangalore, have worked on an **exact probability distribution for the two-tag displacement in a single-file motion** [J. Stat. Mech. (2015) P07024]. They consider a gas of point particles in single-file motion or, in other words, moving on the one-dimensional line with a hard-core inter-particle interaction that prevents particle crossings. The individual particle dynamics can be arbitrary and they only interact when they meet. Starting from initial conditions such that particles are uniformly distributed, the authors observe the displacement of a tagged particle at time t, with respect to the initial position of another tagged particle, such that their tags differ by r. For r = 0, this is the usual well-studied problem of the tagged particle motion. Using a mapping to a non-interacting particle system, Sabhapandit and Dhar have computed the exact probability distribution function for the two-tagged particle displacement, for general single particle dynamics. As by-products, they also compute the large deviation function, various cumulants and, for the case of Hamiltonian dynamics, the two-particle velocity auto-correlation functions.

During the previous year, **Sabhapandit** and **Deepak Gupta (PhD student, RRI)** have been working on **fluctuation theorem for entropy production of a partial system in the weak coupling limit**. Small systems in contact with a heat bath evolve by stochastic dynamics. They show that when one such small system is weakly coupled to another one, it is possible to infer the presence of such weak coupling by observing the violation of the steady state fluctuation theorem for the partial entropy production of the observed system. The authors further propose a general mechanism due to which the violation of the fluctuation theorem can be significant, even for weak coupling. They then go on to analytically demonstrate that this mechanism can be realized by applying an external random force to a realistic model system. In other words, they have found a new fluctuation theorem for the entropy production of a partial system in the limit of weak coupling.

Joseph Samuel's area of professional research interest lies broadly in theoretical physics and specifically in exploring the foundational principles of quantum mechanics and quantum gravity.

During the period 2015-16, his work in the former area used the idea of inherent coarseness in practically any detection process to arrive at a non-trivial conclusion. It appears that such measurement processes on a quantum system can result in a non-unitary evolution of the system. His collaborators in this project were **Anirudh Reddy (PhD student, RRI), Kumar Shivam (PhD student, RRI) and Supurna Sinha (RRI).** The related publication is **Coarse Quantum Measurement: An analysis of the Stern-Gerlach experiment**, Physics Letters A, 380, 1135 (2016).

Motivated by the fact that simple Euclidean methods can successfully reproduce entropy and temperature of black holes derived by completely different methods, Samuel has used a rotated time direction on a standard Wick rotation to arrive at a real Euclidean matrix for describing a rotating black hole.

The standard Wick rotation rotates the time coordinate, which in some cases leads to complex metrics. In this work, Samuel has rotated the time direction instead and arrived at real Euclidean metrics, while maintaining the successes of the Wick rotation procedure. The paper explores a local notion of Wick Rotation in each tangent space. The idea of trivial holonomy is used to impose the condition of zero angle deficits. The final result is a formulation in which rotating black holes can also be described by a real Euclidean metric. The related publication is **Wick Rotation in the Tangent Space**, Classical and Quantum Gravity 33, 105006 (2016).

Berry and Wilkinson's early paper on diabolical points for a quantum system in a confined region with a variable shape showed that such shape changes can lead to a change of sign of the wave function, very similar to that found in molecular physics. Motivated by this result, **Samuel** and his collaborators Paolo Facchi, Giancarlo Garnero [Université di Bari, INFN, Italy] and Giuseppe Marmo [Université di Napoli, INFN, Italy] have analyzed the existence of a non-trivial Berry phase associated with

the dynamics of a quantum particle in a box with moving walls. The work aims to show that a suitable choice of boundary conditions has to be made in order to preserve unitarity. The unboundedness of the Hamiltonian describing the system will lead to a natural prescription of renormalization for divergent contributions arising from the boundary. Titled **"Moving Walls and Geometric Phases"** and submitted for publication in Annals of Physics, Samuel's paper treats the more general boundary conditions compatible with unitarity and scale changes. The authors have also found the Berry curvature and noted its connection with the Poincare metric.

Supurna Sinha's research is related to theoretical physics.

During the year gone by, she has been working on **coarse quantum measurement** in collaboration with **Anirudh Reddy (PhD student, RRI), Kumar Shivam (PhD student, RRI)** and **Joseph Samuel (RRI)** [Physics Letters A, 380, 1135 (2016)]. The work involved an analytical study of the quantum measurement process in the context of the Stern-Gerlach experiment. The spin of a silver atom was regarded as the quantum system in question and its position was viewed as the measuring apparatus. Both the system and the measuring apparatus were treated exactly and quantum mechanically using unitary evolution via the Schrodinger equation. The fundamental idea used is that the probes that determine the position of the silver atom, no matter how sensitive, are still limited in resolution. The result observed shows an apparent non-unitary evolution of the spin, so that a pure density matrix appears to evolve to an impure one due to the coarseness of the detection process. Apparently the coarse measurement of position yields information about the spin state and quantifies the information thus gained. A Wigner function matrix approach was used to elucidate these ideas.

Sinha and Sebanti Chattopadhyay, (VSP student, RRI) have worked on the **ring closure probability of semiflexible polymers** in the past year. In this work, the ring closure probability of semiflexible polymers is investigated within the Worm Like Chain (WLC) model. The semi-analytical results show a power-law decay in ring closure probability with the contour length of the polymer over a range of length scales. The qualitative behavior agrees with recent Hi-C experiments where a `scale free' organization is noticed in chromatin over long strands of chromatin. The predictions can be tested against future smaller scale single molecule ring closure experiments on DNA and actin filaments.

Sinha has also worked on **diffusion at low temperatures** with **Urbashi Satpathi (Postdoctoral fellow, RRI)** during the period 2015-16. In the study, diffusion at low temperatures is investigated using a realistic response function, which can be realized in a laboratory in the context of optical molasses. A quantum version of the law of diffusion based on the fluctuation dissipation theorem is being drawn up in this work. The work shows that the logarithmic law of diffusion in the quantum domain is robust and does not depend on the details of the choice of the response function. The new response function also has the additional advantage of fixing certain inconsistencies that show up in the expression for the mean squared displacement with the step function response function used in an earlier study.

Sumati Surya works in quantum and classical gravity.

Covariant observables in quantum gravity are her first topic of research with collaborator, Rafael Sorkin (Perimeter Institute, Canada) during the year gone by. A quantum sequential growth (QSG) model of causal set quantum gravity is a quantum analog of a classical stochastic process in which a causal set is grown element by element starting from a single element. The simplest example of a QSG model is complex percolation, characterized by a single complex parameter q. The growth dynamics gives rise to a quantum measure over labeled, finite time events, which are themselves not covariant. In order to construct covariant observables the quantum measure in itself must be extended to infinite time events – something that is not always guaranteed. Using Sorkin's method of canonical approximants, **Surya** and Sorkin obtain the quantum measure for an important class of covariant observables in complex percolation. These include the originary or big bang event as well as post or bounce events. They find that there are precluded or zero measure events for certain values of q, which is a first step to making predictive statements in causal set quantum gravity.

With Lisa Glaser (Nottingham University, UK) and Denjoe O'Connor (DIAS, Ireland), **Surya** has worked on the **large N limit in 2D causal set quantum gravity** [The Hartle-Hawking wave function in 2d causal set quantum gravity, L. Glaser and S. Surya, Class.Quant.Grav. 33 (2016) no.6, 065003]. 2D causal set

quantum gravity exhibits a remarkable phase transition from a continuum phase to a crystalline non-continuum phase as was shown in earlier work in 2011. This phase transition can play a non-trivial role in determining the Hartle Hawking ground state as the authors have recently shown. Much of the analysis, however, was done for a fixed system size and the question is whether the effect is due to the finite size of the system. Using the RRI HPC cluster, they have now analyzed this phase transition in detail for a wide range of system sizes and coupling constants. The results show that it shares some features with a first order phase transition for a large range of values of the coupling constant. Analyzing the scaling behaviour they find that a rescaling of the temperature with the system size leads to a well-behaved collapse indicating that the phase transition survives the large N limit.

With Fay Dowker (Imperial College, London) and **Nomaan (PhD student, RRI)**, **Surya** has also been working on **the discrete propagator in curved spacetime**. Constructing a local Green's function for a scalar field on a causal set is non-trivial, partly due to the non-locality inherent in a continuum like causal set. An ansatz for the retarded massive scalar field Green's function was proposed by Johnston in 2 and 4 spacetime dimensions using discrete paths and assigning amplitudes for “hopping" and “stopping". This ansatz reproduces the spacetime Green's function for a certain choice of the hopping and stopping amplitudes. The simplicity of this prescription is very appealing and it is therefore of interest to see if it survives in all dimensions and in the presence of curvature. Using Riemann Normal Coordinates they have shown that in 2D and in certain special cases in 4D, they find that this is indeed the case. They hope to use this to find the curved spacetime Sorkin-Johnston ground state.

Madhavan Varadarajan's areas of professional research interests lie in classical and quantum gravity.

A note on entanglement entropy, coherent states and gravity [Gen.Rel.Grav. 48 (2016) no.3, 35]. – **Varadarajan**'s major research this year involves using the idea that the entanglement entropy of a free quantum field in a coherent state is independent of its stress energy content to highlight the fact that while the Einstein equations for first order variations about a locally maximally symmetric vacuum state of geometry and quantum fields seem to follow from Jacobson's principle of maximal vacuum entanglement entropy, their possible derivation from this principle for the physically relevant case of finite but small variations remains out of reach. Independent of unknown Planck scale physics, he also applies this result to the context of Bianchi's identification of the first order variation of Bekenstein Hawking area with that of vacuum entanglement entropy. The argument is that under certain technical assumptions this identification seems not to be extendible to the context of variations to coherent states that are finite but small. His particular method of estimating the entanglement entropy variation reveals the existence of certain contributions over and above those appearing in Jacobson's and Bianchi's works. He discusses the sense in which these contributions may be contradictory to those already established in this area.

Varadarajan has also been working on **quantum dynamics and long distance correlations in polymer-parameterized field theory** this past year. A satisfactory quantum gravitational dynamics must encode long distance propagation effects so as to possess a physically relevant classical limit. Current proposals for quantum dynamics in Loop Quantum Gravity (LQG) do not seem to encode such effects. The issue is analyzed in the context of a field theoretic toy model for gravity known as Parameterized Field Theory (PFT), for which a rigorous LQG type quantization was constructed earlier by Alok Laddha (Chennai Mathematical Institute) and Varadarajan. They show how to define the quantum dynamics for PFT so that it encodes long distance propagation effects. The lessons learnt from this work are expected to be of use when scaled up to full-blown LQG.

RESEARCH FACILITIES

Research Facilities of the Institute are composed of five sections – Electronics Engineering Group, Soft Condensed Matter Group Labs, Mechanical Engineering Section, Library and Computer Section. These are staffed by domain experts in specialized engineering, computing, laboratory instrumentation, test and measurement apparatus and library science. These sections are aimed at enabling the research, including theoretical, computing, observational and experimental. The domain experts are a mix of scientific staff and technical staff, who participate in research projects as part of research teams as well as provide specialized knowledge and services to the various research projects undertaken in the Institute.

Electronics Engineering Group

Electronics Engineering Group **or EEG** has skilled electronics engineers, in analog, RF and digital electronics, which are capable of conceptualizing, designing, developing and testing complex circuits, customized for special research requirements. One of the major activities of EEG is the design, development and testing of receivers for radio astronomy. RRI has a long history in the design and development of a variety of analog and digital systems (receivers, spectrometers, correlators) that have improved the capabilities of national and international telescope facilities. The group has designed and built feeds, wideband antennas as well as standard and special-purpose front-end receiver systems operating at wavelengths from decameter to millimeter. Over the years, the engineers have acquired expertise in the development of FPGA based digital systems.

EEG is equipped with modern measurement and testing devices for analog and digital electronics. It has fabrication and testing facilities for RF systems, a PCB engraver, and modern CAD design packages for the development of Antenna and FPGA systems. EEG is also fully equipped for the development and testing of X-ray astronomy instrumentation. The infrastructure includes a clean room, X-ray generator, beamline, polariser and monochromator, vacuum systems, mounts and electronics for the evaluation of the performance X-ray detectors and associated instrumentation.

The major research projects that EEG has been involved in and actively participated in developing during the year 2015-16 are:

SARAS-2 and APSERa – radiometers aimed at detection of CMB distortions

SWAN – a distributed networked antenna array for the emerging field of cosmic radio transients

POLIX – an X-ray Polarimeter that is to be the payload for ISRO's XPoSAT mission.

Triple-slit experiment testing quantum mechanics at radio wavelengths along with assisting many of the experimental laboratories and projects in Soft Condensed Matter, Light & Matter Physics, and Astronomy & Astrophysics. EEG members also engage in strategic developments aimed at capacity building that maintains competitive edge of the experimental research of the Institute. EEG has also worked towards development of Brain-Computer Interface as a primarily societal service in the Indian context.

1. SARAS 2

R Subrahmanyan, N Udaya Shankar, Saurabh Singh, S Mayuri, A Raghunathan, R Somashekar, Srivani K.S., Girish B.S. and several Visiting Students and Research Assistants.

Shaped Antenna Measurement of the background radio spectrum – SARAS, is a project to precisely measure the cosmic radio background and faint features in the sky spectrum at longer wavelengths (7.5 – 1.2 m) that arise from redshifted 21 cm from gas in the Cosmic Dawn and Epoch of Reionization. The present stage of the project is called SARAS 2. As part of SARAS 2 project, the wideband receiver system consisting of

i) A Non-Resonant wideband shaped spherical monopole antenna

ii) A thermally well designed front end receiver system with self calibration facility and

iii) An FPGA based precision spectrometer was built and commissioned in 2015-16, and is currently undergoing field trials for science data and performance data that feeds into further improvements. Separately a system to measure the Radio Frequency Interference (RFI) at potential sites where we may deploy SARAS 2 has been built and this has been used to test sites in the Nilgiris, across Eastern and Northern Karnataka, and in Ladakh.

2. APSERa

R Subrahmanyan, N Udaya Shankar, S Mayuri, A Raghunathan, R Somashekar, Srivani K.S., Girish B.S. and several Visiting Students and Research Assistants.

The Array of Precision Spectrometers for the Epoch of Recombination – APSERa – is a courageous, path-breaking and challenging project to detect recombination lines from the Epoch of Cosmological Recombination. This project envisages an array of small telescopes that are purpose built to detect a set of adjacent lines from cosmological recombination in the spectrum of the radio sky in the 2-6 GHz range. As part of the project, a profiled discone antenna operating in the frequency range 2-4 GHz, an I/Q signal front end receiver with an analog bandwidth of 2 GHz, and a high-speed sampler and FPGA-based digital spectral receiver has been developed in 2015-16.

A.Raghunathan, Divya Shankar (Visiting student): The Detection of the Epoch of Recombination signal in the frequency range 2-4 GHz requires a feed antenna with frequency independent radiation and impedance characteristics. In addition, the antenna also should have minimum response to ground radiation. Keeping in view these requirements, a ridge loaded cavity backed shaped slot antenna has been designed. The structural parameters were optimized using WIPL-D, which is electromagnetic simulation software, to meet the desired characteristics. A prototype is being constructed to validate the design.

3. SWAN

Avinash A. Deshpande, K.B. Raghavendra Rao, Srivani K.S., Kamini P.A, Vinutha, Sandhya, Mamta T.S and several Visiting Students.

RRI scientific staff is engaged in design, building and commissioning – with substantial involvement of university students – a broad-band Sky Watch Array Network (SWAN) for radio astronomical studies. This is a Radio Telescope with widely distributed sensors, operating over the frequency band 50-500 MHz. The main objectives of SWAN are to i) conduct searches and studies of fast radio transients and ii) high-angular-resolution radio imaging of the long-wavelength sky, while enabling active participation of students across research institutes in India in all aspects of SWAN. For this activity both broadband and narrow band receivers are being developed.

a. Broad-band Receiver System: A prototype low–noise amplifier with FM band rejection has been developed for sky observations in the frequency range 50-500 MHz, with SWAN and similar radiometer systems, in the presence of strong RFI environment. The amplifier has 20 dB gains with 3 dB droop across the band, 40 dB FM signal rejection and 0.6-1.1 dB noise figure. An eight input digital receiver having full Stokes measurement capability and with 512 spectral channels over a bandwidth of 200 MHz is realized using a ViQuad board consisting of high-speed ADCs and Virtex-6 FPGA. In 2015-16 the firmware development for Stokes computation was completed and the hardware evaluation of the SWAN Digital Receiver (SwDR) is under progress.

b. Narrow band Receiver System: Phase 0 of SWAN (Sky Watch Array Network) project made extensive re-use of GBT-RRI MBR system. Each of the multiband receivers was connected to eight independent bow-tie antenna arrays, and all were configured to operate over a similar RF band. A GPS disciplined Rubidium oscillator was used to discipline all the local oscillators of the receiver systems. In addition, to enable observation in the presence of FM signals, FM signal rejection filters were incorporated in every front end receiver. The data collected in the each of the receivers was used for testing the software correlator being developed.

4. X-ray Polarimeter (POLIX for the ISRO XPoSAT mission)

Biswajit Paul, Rishin P.V., Gopala Krishna M.R., Varun, Mohammed Ibrahim, Rajagopala G., Pooja Verma, Sandhya P., Nagaraja H.N., Achan Kunju

There are two X-ray Polarimeter development related activities currently going on at the X-ray lab. They are (a) Thomson X-ray Polarimeter - POLIX and (b) Photo-electron Polarimeter.

a) Thomson X-ray Polarimeter - POLIX

POLIX is an X-ray polarimeter working in the energy band of 5-30 keV on the principle of Thomson scattering. A dedicated small satellite mission of ISRO, named XPoSat has recently been approved with POLIX as the scientific payload. Work for the satellite has been initiated in ISRO Satellite Centre and our interactions for various payload interfaces are ongoing.

The mechanical configuration of the polarimeter consists of four X-ray detectors, placed on all sides of a scattering element. X-rays from cosmic sources are allowed to fall on the scatterer through a collimator which restricts the field of view of the instrument. Currently most of the instrument sub-systems are in the Engineering model development phase.

On the detector front, the main emphasis in the year 2015-16 was to prepare one detector for the vibration test, so that its reliability can be established. This involved epoxying and fixing the feedthroughs and brass rings on the detector housing. The wireframe was assembled in the housing, and the assembled detector was checked for leakage, temperature cycled and gas filled. Currently, the detector and the jig are completely ready for carrying out vibration tests.

In order to measure the actual collimator response, a collimator calibration jig has been fabricated (see figure below), which can scan the collimator in front of an X-ray source at different angles. The heavier parts of the unit were fabricated by an external vendor and the precision parts were fabricated in-house at the Institutes' Mechanical Engineering workshops.

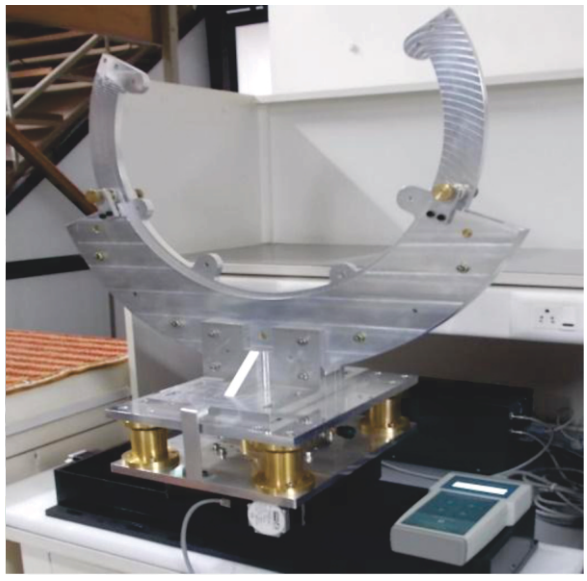


Fig: Jig for calibration of the Collimator for the X-ray polarimeter

On the electronics front, the emphasis in 2015-16 was to convert laboratory model versions of electronics to pre-engineering model versions.

For the Front End (FE) electronics, one more unit of the Front end test box with upgraded circuit was fabricated and tested. For the Processing Electronics (PE), the PE analog and digital cards were fabricated and preliminary tests have been carried out. The schematic design of a back plane card which will be used along with these two cards was also designed and fabricated.

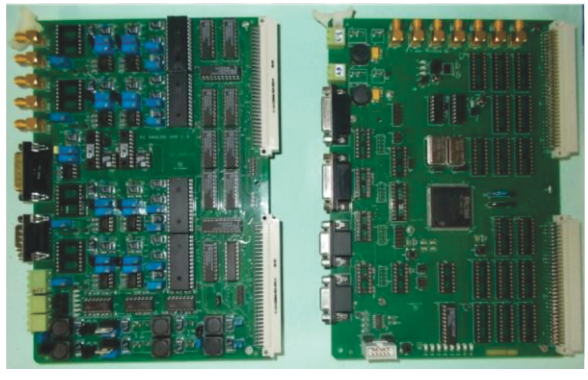


Fig. PE analog and PE digital cards for the X-ray polarimeter.

For the Common electronics (CE), schematic design of the pre-engineering model card was taken up. The redundancy related aspects required for the system has also been incorporated in the design of this card.

As a part of space qualification of the HV unit used in the FE, a thermovac test is planned. A thermovac test jig is being developed in which the high voltage unit will be placed in a vacuum chamber, with the electronics for control of the high voltage unit placed externally. USB based control and data acquisition is used for the thermovac test jig. For this purpose, a commercial USB data acquisition system was procured and preliminary tests have been carried out.

b) Photo-electron Polarimeter

This project involves development of a new technique for polarisation measurement. The instrument is based on the principle that the direction in which the photo-electron is ejected in a gas is sensitive to the polarisation of the photon that caused the photo-electron ejection.

During the 2015-16 year, a new wireframe with reduced inter-wire distance of 2.4 mm was fabricated, assembled in the housing, leak checked, gas filled and tested. The detector was set up for polarisation experiment and data was acquired with non-polarised source as well as polarised source at different angles and gas pressures. Figure below shows the polarisation test setup. The results of the polarisation tests are encouraging.

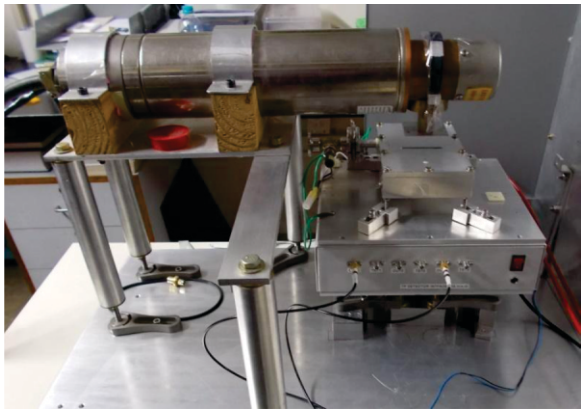


Fig. Test setup for proof of concept of the Photo-electron polarimeter

A standalone USB based data acquisition system is being developed for the Photo-electron polarimeter. The existing Processing electronics card for POLIX in conjunction with a commercial FPGA kit is used so as to attain USB based data acquisition. Development of VHDL firmware for the FPGA cards as well as the software used at the PC end for USB based data acquisition is in progress.

5. Brain Computer Interface

Hema Ramachandran, B. Ramesh, Sujatha S., Arasi Sathyamurthy, Somashekar R., Raghavendra Rao K.B., Mohammed Ibrahim, Junaid Ansari, and visiting students

This project applies the expertise of the Electronics Engineering Group, which has been developed over the years of engagement in experimental physics and astronomy, to make an impact on a key problem in society, with a solution appropriate in the Indian context. The project is aimed at enabling control by diabled individuals using directly EEG sensing brain computer interface (BCI).

The group conducted various Steady State Visually Evoked Potentials - SSVEP based BCI experiments to optimize the sensor performance and calibration protocols using a Bio-signal amplifier. To improve the portability of the systems being developed at the Institute, surface mount device (SMD) based Bio-signal amplifier has been developed with i) reduced via holes, ii) a pair of 50 Hz notch filters to suppress the power line radio frequency interference, iii) a 2-35 Hz band pass filter and iv) stages of voltage amplifications. In addition, essential circuitries like automated gain and offset level adjusters are also implemented. The achieved voltage gain of the Bio-signal amplifier is about 10^6. Passive electrode optimization for its performance is being carried out. Experimental protocol has been developed for spatial and frequency calibration of stimuli LED patterns.

An analog Matched Filtering system for SSVEP detection has been developed. The system consists of a frequency generation board and processing board. The frequency generation board generates the template sine-wave frequencies in the range 10 -24 Hz to form the stimuli for the subject. Each of these stimuli frequencies is mapped to a certain BCI command. The matched filter board processes the evoked SSVEP signal from the brain and outputs the decision based on matching of the stimulated frequency with the template frequency. The system has been evaluated in trial runs and demonstrated to work well with the photo-detector input.

An open-source voice command interface kit has been developed by integrating open-source software and

inexpensive hardware components. The software for the kit has been developed as a modular framework with replaceable components. It also provides support for C++ library based applications as a higher level programming platform. The usefulness of the kit was demonstrated by applying it to voice-steer electric wheelchair. A paper entitled - An Open Voice Command Interface Kit, has been published in the IEEE transactions on Human Machine System.

6. Strategic and Engineering Developments

(a) Miniature Portable Dual Receiver: PDR-M2

Avinash A. Deshpande, K.B. Raghavendra Rao, Srivani K.S., Kamini P.A, Vinutha, Sandhya, Mamta T.S and several Visiting Students Miniature Portable Dual Receiver was developed as a complete receiver system built for providing hands-on experience to undergraduate and post-graduate students. The front end and back end receivers are made compact and with dual polarization capability so that they could be transported easily from place to place for remote sky observations. The receiver operates over the band 100-1000 MHz with an instantaneous bandwidth of 14 MHz centred at an IF frequency of 140 MHz. The Digital backend receiver is built using low-power, 8-bit dual-channel ADCs (AD9288) and Virtex-5 FPGAs. The data is processed on-line and full four stokes parameters are generated.

SCM Group Labs

Chemistry Lab





This lab has state-of-the-art facilities necessary for the synthesis of liquid crystal materials, nanoparticles and other organic and organometallic compounds. Major equipment in the lab includes a microwave synthesizer, rotary evaporators, vacuum pumps, magnetic stirrers with hot plate, etc. Several hundred molecules have been synthesized in the Chemistry Lab.

Analytical Lab

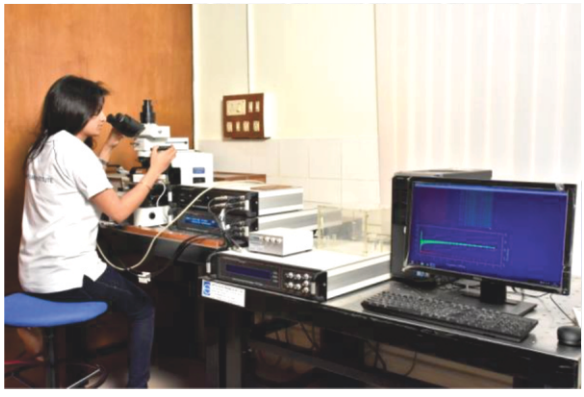




This lab has many modern facilities necessary for the characterization of materials. Major equipment in the lab includes polarising optical microscopes, differential scanning calorimeter, elemental analyser, and thermo

gravimetric analyser, infrared and UV-visible spectrophotometer.

Microscopy and Dielectric Spectroscopy Lab



This lab is equipped with a high performance dielectric measurement system along with multi-electrode test interfaces and a high voltage booster for studying broadband dielectric spectroscopy of liquid crystals and polyelectrolytes. Optical polarizing microscopes integrated with a spectrometer and an experimental setup for studying electro-optics are used in the investigation of phase transitions, defects, switching properties and field induced effects in liquid crystals and liquid crystal nanoparticle composites. These studies can also be combined with three dimensional imaging using a confocal microscope.

Phase Transition and Electro - Optics Lab



The soft condensed matter phases of novel Mesoscopic molecules and their physical properties are investigated both experimentally and theoretically in this lab. The objective is to understand the molecular organization in these phases and look for novel macroscopic properties of these systems.

Liquid Crystal Display Lab



The LCD lab has basic facilities for the fabrication of liquid crystal cells and small size (100mm X 100mm) displays as well as standard electronics equipment for their testing. Spin coating system, vacuum deposition unit, rubbing machine and temperature controlled ovens are frequently used by the lab members.

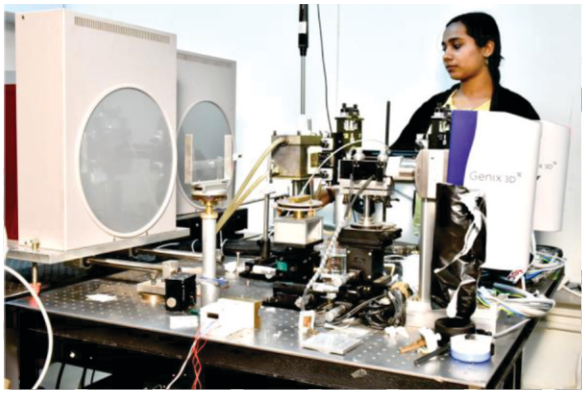
Rheology and Light Scattering Lab



The lab utilises rheology and lightscattering techniques to study the dynamics of soft glassy materials and amphiphilic systems. The most frequently used instrumentation in the lab includes a dynamic light scattering setup, an acoustic and electroacousticspectrometer, a high speed CMOS camera and a rheometer. Rheology, dynamic light scattering, high-speed imaging, ultrasound attenuation and colloid vibration current measurements are some of the measurement techniques used in the lab.

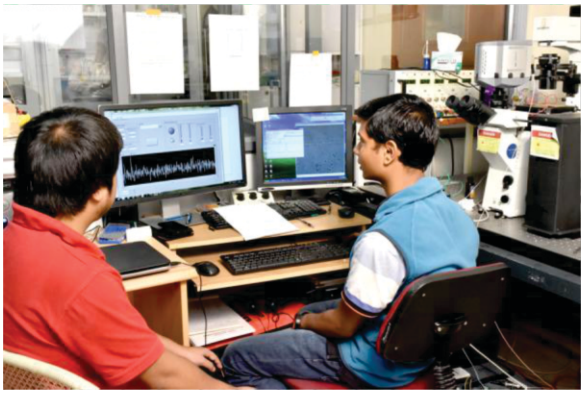
X-Ray Diffraction Lab





The X-ray lab is well equipped for studying the structure of soft matter systems. Facilities available include a powder diffractometer and small-angle scattering instruments. Data can be collected from both oriented and powder samples, over a range of temperatures from 0° C to 250° C.

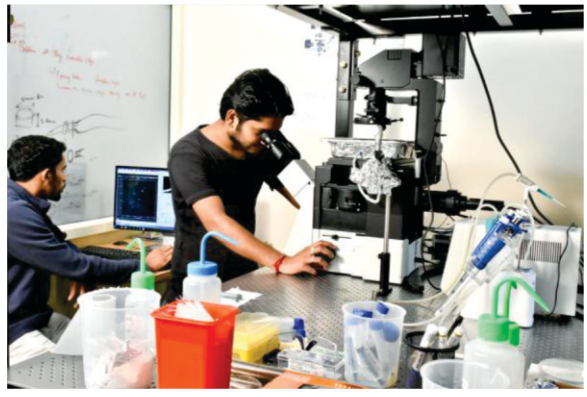
Biophysics Lab





The Biophysics lab is a self-sufficient lab where various cells can be grown, manipulated and analysed. It is equipped with two fully motorized microscopes allowing for fluorescence and phase-contrast microscopy measurements, confocal microscope, biosafety cabinet for growing cells, incubators, centrifuge and a 3D microscope for dissections. Apart from these there are ultrasensitive force measurement setups like laser based Optical Tweezers and an in-house developed optical fiber based force apparatus for studying mechanical properties of neuronal cells.

Nanoscale Physics of Soft and Living Matter Lab





This lab fabricates nanoscale devices to study role of intermolecular interactions in soft matter as well as in biological systems. The aim is to understand their structure function relationship, at single molecule resolution. Common instrumentation developed in the lab are a state-of-the art nanopore rig to measure translocation of single bio-molecules through nanopore devices, gel electrophoresis systems, visualization inverted microscopes and a bioclean DNA and protein workstation. This lab is fast growing to include two more optical setups; one for low noise laser optical tweezers coupled to nanopore platform and the other a single molecule resolution TIRF microscopy setup.

Electrochemistry and Surface Science Lab



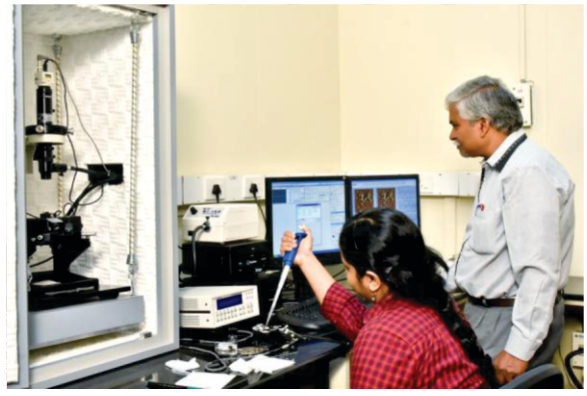
The lab performs controlled experiments on test surfaces in electrochemical cells using electrochemical instruments such as potentiostats, frequency response analyzer and lock-in amplifier. An electrochemical quartz crystal microbalance is used to measure mass changes on the surface in situ. Characterization studies of organic thin films are carried out with a variety of surface probe techniques like scanning tunneling microscopy, atomic force microscopy, scanning electron microscopy etc.,

SEM Lab



The SEM lab is equipped with a field emission scanning electron microscope (FESEM). The FESEM has a scanning transmission electron microscope (STEM) attachment that can be used for imaging nanomaterials as well as an energy dispersive X-ray spectroscope (EDX) to identify elements and the surface composition. The FESEM has a local charge compensation mode to enable imaging of non-conducting surfaces and very low voltage operation mode for organic thin film studies. The microscope has a cryo-microscopy attachment to enable imaging soft materials by freeze-fracture method at liquid nitrogen temperatures. The FESEM is being used extensively for studies of nanomaterials, polymers, liquid crystal nanocomposites and soft matter.

AFM Lab



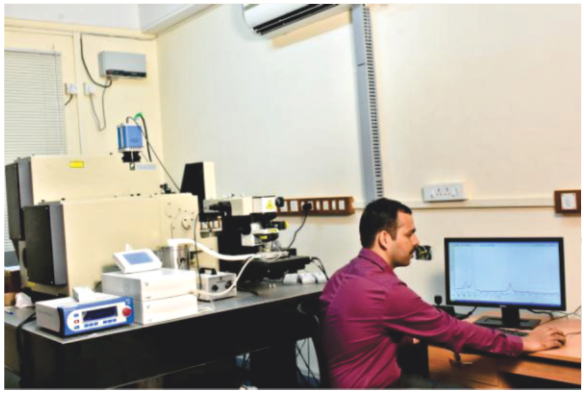
The AFM lab is equipped with Atomic force microscope with several additional features such as STM, conductive AFM, magnetic force and electric force microscopes with built-in temperature controller and environmental chamber. This microscope is used for the surface studies of organic thin films, liquid crystals, graphene materials, nanocomposites and soft materials both on conducting and non-conducting substrates.

NMR Lab



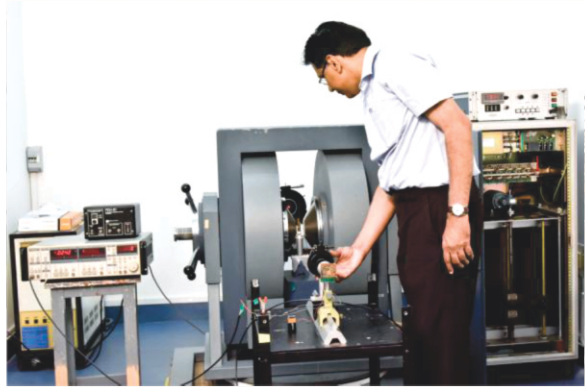
The NMR lab is equipped with a 500 MHz high resolution (Bruker) Nuclear Magnetic Resonance spectrometer with a built-in temperature controller. This spectrometer is mainly used to identifymolecular structures using ^{1}H and ^{13}C NMR chemical shifts. Surfactant molecule association with the nanostructures in dispersed surfactant solutions as a function of temperature is also studied using this spectrometer. 2D NMR and spin-lattice relaxation time experiments can also be carried out.

Micro-Raman Spectroscopy Lab



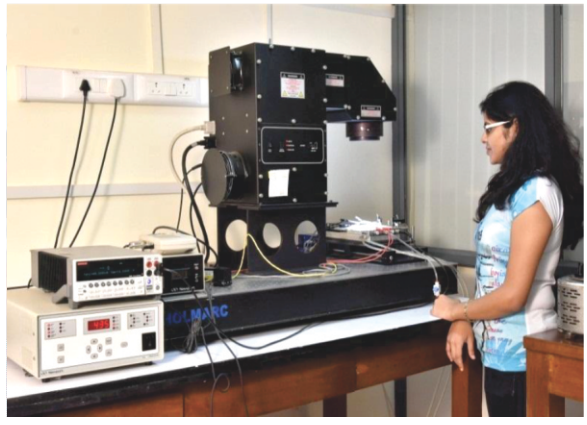
The micro-Raman Spectroscopy Lab is equipped with a state of the art Triple Raman spectrometer with different laser sources with wavelengths from IR to UV range. The setup is also equipped with a microscope hot stage to study samples at differenttemperatures from -180^{o}C to 300^{o}C. The micro-Raman mapping of the samples can be carried out using a XYZ nano positioning stage. Raman Spectroscopy is a sensitive and non-invasive technique to recognize and characterize chemical substances within the samples. Small volume of samples can be analysed to detect the presence of compounds predominantly by the presence of specific chemical bonds. The Micro-Raman spectrometer is being used for studies of nanomaterials, polymers, liquid crystals, nanocomposites, bio-materials and other soft matters.

Magnetic Studies Lab



The Magnetic studies lab is equipped with a 2 Tesla electromagnet with adjustable pole gap and a Faraday balance system with a built-in temperature controller. The Faraday balance is used to study the diamagnetic susceptibility (~10^{-7}cgs) of thermotropic and lyotropic liquid crystals, micellar solutions and liquid crystal nanocomposites, as a function of temperature. An in-house built high-resolution optical birefringence (10^{-7} radians) set up is used in conjunction with the electromagnet to study the magnetic birefringence of soft materials. Magneto electrochemistry measurements are also carried out in this lab.

Photophysical studies Lab



The Photophysical studies lab has two major instruments; solar simulator and photo electrochemical work station. These instruments are used to study photophysical properties of materials.

Mechanical Engineering Services (MES)

The Mechanical Engineering Services division at the Raman Research Institute (RRI) has for long been committed to provide quality services to the various departments' needs at RRI. The MES primarily coordinates and assists in all the mechanical jobs for various divisions of RRI, including for the development of research and experimental apparatus and for improvements of the campus infrastructure.

The Mechanical Engineering Services (MES) division offers services such as product conceptualization, design & development, engineering and fabrications using a variety of materials, carpentry and painting.

During the 2015-16 year, MES has engaged in a variety of mechanical engineering; samples of processes are shown in the figures below.



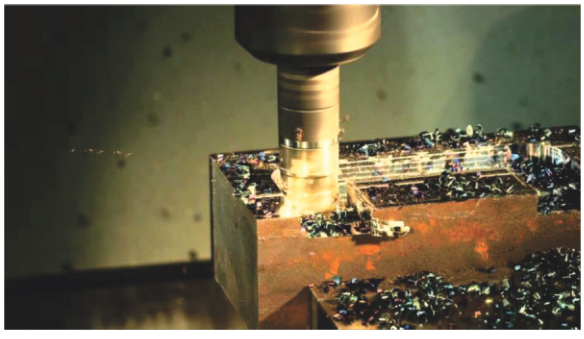


Figure: Machining / Milling based fabrications

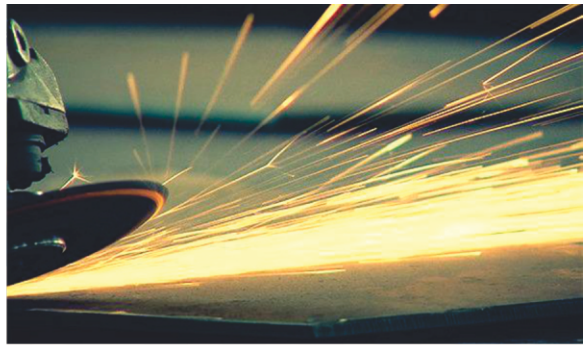


Figure: Grinding based surface treatment

MES has in the last year been involved in several projects that have required mechanical design, and has often participated in the activity from the development of the concept through design and fabrication. Examples are given in the figures below.

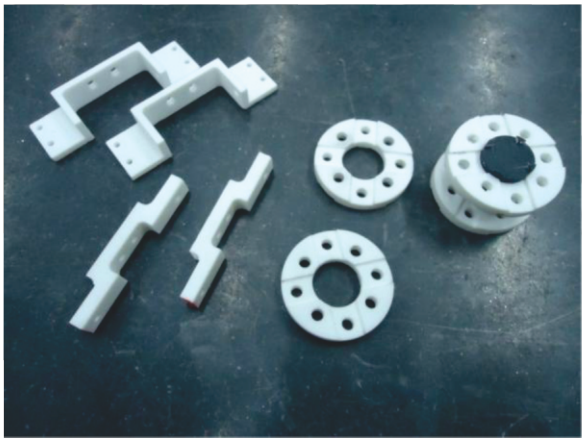




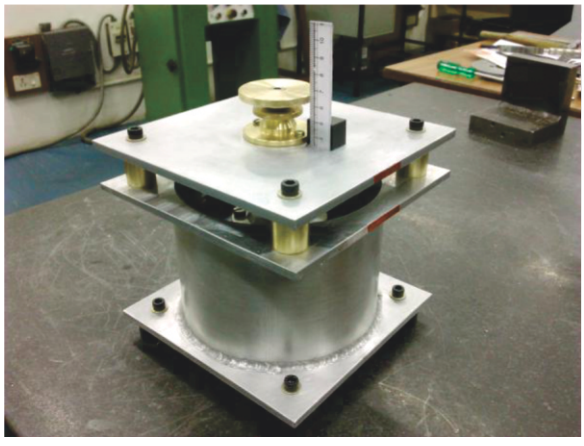
Alumunium Hood Camera Mount for Biophysics Laboratory (Gautam Soni)



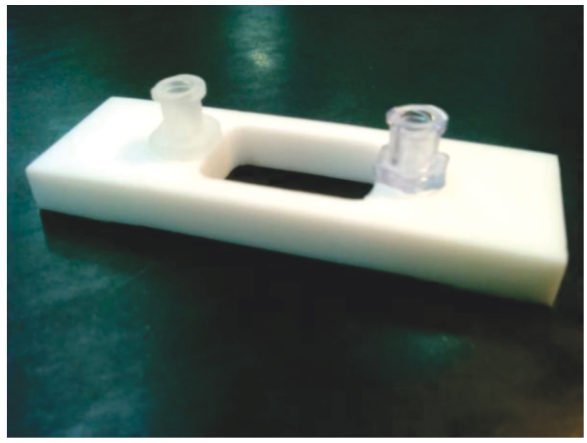
Pyramidal Horn Antenna as part of the Strategic Development activity (AA Deshpande)

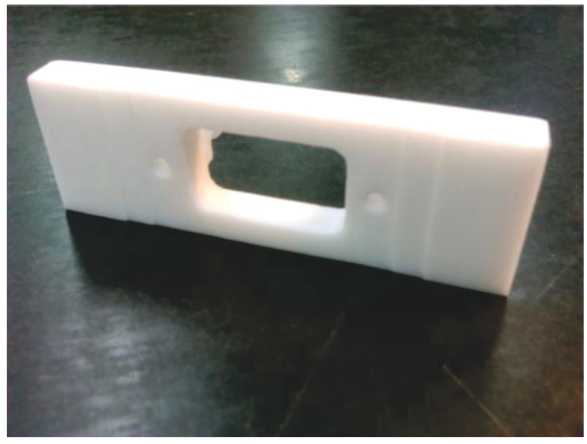


Ceramic components fabricated for the cold ion experimental setup (Sadiqali Rangwala)

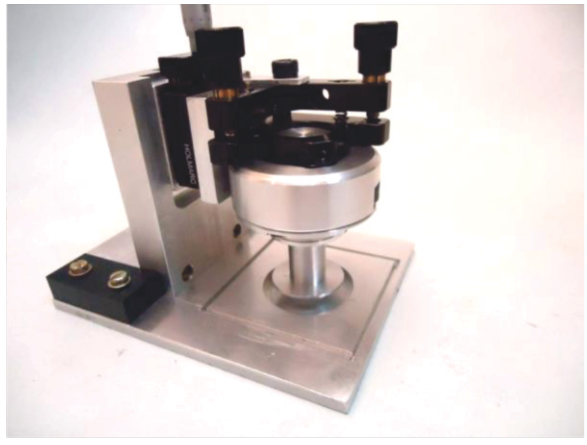


High Q cavity for the experimental coupling interaction between Rb atomic systems with pair of laser transitions & a microwave cavity field (Andal Narayanan)

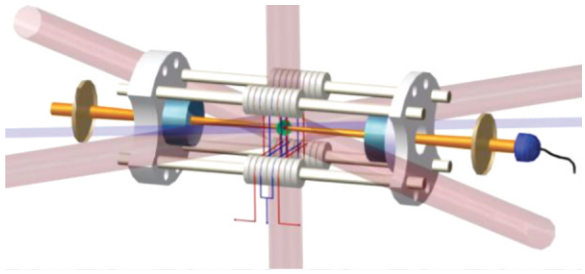




Teflon Coverslip holder for Biophysics Laboratory (Gautam Soni)



Shear cell experimental setup for biophysics of cell structure (Pramod Pullarkat)



Concept design for an atom cavity experiment for Quantum atom optics (Sadiqali Rangwala)



Fresnel antenna fabrication with a test setup (Ramesh Balasubramanyam)

Library

The Institute Library was founded by Sir C V Raman and initially started functioning with his personal collection of books and journals. Today the library has grown and evolved into a modern library consisting of print as well as electronic information resources. All the functions and transactions of the library have been automated using LIBSYS – Library automation software. Recently, the library software has been upgraded to Version 7 in an effort to keep it modern and provide ease of use of the resources to the user community and also library staff.

The library is the node for information resources at the Institute, providing general and also specialized information to its users. Currently, the library has total collection of 69551 items of books and bound volumes of journals. Of this, 28598 are books and 40953 are bound volumes of journals. The library subscribes to 92 e-journals, 53 Print only and 3 Print+Online journals. Additionally, the library has 1793 non-book materials that include scientific slides, CD-ROMS, DVD's and Audio/video tapes.

Our continued partnership with the National Knowledge Resource Consortium has provided to our user community of scientific and technical staffs online access to 4600 journals published by 15 publishers. The library web pages have been continually upgraded to provide a single-window access to all the information resources, including online resources of the consortium.

Digital Library Activities

The RRI Digital Repository (RRIDR), also called as e-sangrah, is the official Institutional Repository. This repository, which is built on the Dspace platform, is open source software and is upgraded to the latest Version 5.4. Scholarly publications of RRI are uploaded regularly to this repository. Digitization of archival materials, photographs and audio/video is continuing from previous years. They are all uploaded on RRIDR. Theses submitted by RRI PhD students are also uploaded on the repository. The number of uploads during the year 2015-16 is 630 and the total number of records on RRIDR is 7802.

The Imprints collection of the Institute is a unique bio-bibliographic database that has expanded to include the profiles of all those scientists who have left RRI to pursue assignments elsewhere and have left behind some imprint in the knowledge base in the form of publications with RRI affiliation. In the year gone by, this database has added profiles of 10 scientists and the total number is 30.

RRI library supports human resource development programs by providing internship training to the students of Bangalore University, Kuvempu University, Shimoga and Shri Jayachamarajendra (Govt.) Polytechnic for Women. During the current year, 10 students from the Library Science departments of these institutions were trained at the Institute library.

During this annual year, the library started a thematic display of books to mark special occasions like Independence Day (August 2015), Dussehra (October 2015), Swami Vivekananda's Birth Anniversary (January 2016) and the International Women's Day (March 2016).

The Institute Library organized the following events in 2015-16:

The National Library Week was marked at RRI on 14th Nov 2015 by organizing a special event on campus. A talk by Prof Uday Shankar on the topic "Exploration of the Universe" was followed by a debate on the topic "Is there a decline in the reading habit in digital age". Four upcoming librarians debated this with participation by the audience.

A BITS and BYTES Special Lecture series talk was organized at RRI on 12th February 2016 in collaboration with NCSI NET, KALA and the Sarada Ranganathan Endowment for Library Science. A Talk was delivered by Mr Chris Kluiters, VP, Springer on the topic "From reading room access to text and data-mining: a journey of e-journal licensing to organizations".

Computer Facilities

The various computing needs of the different groups and departments at Raman Research Institute are handled by the Computer group members. Scientific staff and PhD students have individual computing systems on their desks, in some cases these are portable laptops and otherwise desktop personal computers. Higher performance computing is provided for specialized research via inhouse cluster computing systems with a variety of configurations, which are specially tailored to the variety of research in the Institute. The group also provides and manages services like Email, internet access to the worldwide web, printing, VPN, Digital Repository, among others.

The Campus network upgradation, both wired and wireless network, was completed during 2015-16. The new network is IPv6 enabled. It provides 10 Gbps fiber interconnects between buildings and 1 Gbps wired Ethernet connection to desktops. Wireless network is provided across the campus using dual-band, 802.11b/g/n wireless access points controlled by a Wireless LAN Controller. Wired and wireless network coverage was also enhanced in the last year to keep the system modern, high speed and reliable.

The Computer Group took up the migration of data and successfully migrated the data from the existing DSpace Digital Repository to the latest version of DSpace. It also took up the implementation of the Open Source KOHA Library Management System and migration of the data from existing commercial LMS software - LibSys. A sample data from the present Libsys LMS was imported into KOHA successfully. Work is on to port the complete data from Libsys to KOHA.

An Open Source IT Ticketing System, OTRS, has been implemented and is being used to keep track of the requests made for help with the IT resources in the campus. This has been done with the aim of enabling better and transparent communications between computer services staff and the institute user community. An Open Source IT Asset Management System, OCS-NG, also has been implemented to maintain a central record of the computers and laptops in the campus.

Server Virtualization was carried out using KVM Debian Linux (Open Source) for effective utilization of resources and minimizing the number of physical servers. Servers providing DNS/NIS/DHCP services, the LibSys (Library management software) server, IT Ticketing System and IT Asset Mangement System are deployed as virtual servers.

The campus is connected to the internet and the National Knowledge Network (NKN) via a high speed 1 Gbps link. It is also connected to the internet via a dedicated 10 Mbps link. A 2 Mbps leased line connects the Institute to the field station at Gauribidanur. Users are also provided with VPN access to the LAN.

The high performance computing system at the Institute consists of multi-CPU multi-core systems accessed by users from their desktops through a high speed internal LAN. Application-specific software packages along with development tools are available on these platforms. A cluster computer of 16 nodes, 32 Intel Xeon X5570 processors, 256 GB RAM and 32 TB storage caters to the heavy computation needs of special research.

Campus

The RRI campus is located in the northern part of Bangalore City. The campus covers an area of 20 acres replete with trees and shrubs. The hustle and bustle of the busy metropolis outside is left behind as one enters through the gate. The environment inside is as soothing as can be expected from a campus that has integrated so much greenery within its fold together with the various buildings and laboratories. This serene environment creates the perfect surroundings for the creative work and research activities that go on within the campus.

The campus hosts all the office buildings, laboratories, a canteen and the guest house. But once inside, one is left with the overwhelming impression of being surrounded by a natural garden instead of just feeling that one is on the campus of a renowned research institute. Sir C.V.Raman had landscaped most of the campus and the RRI Trust is proud to enforce policies that protect this unique, natural environment.

The guest house on campus is equipped with all modern facilities to confortably accommodate distinguished visitors and visiting academics including visiting doctoral students. The canteen on campus provides meals to all guests together with lunch and refreshments to all RRI employees and those who work at the Indian Academy of Sciences. Informal meetings, various gatherings, concerts and dinners are usually organized at the Village-an ethnically designed area near the canteen which provides a warm, rustic touch to the overall atmosphere on campus.

The building adjacent to the canteen houses a small clinic where consultant medical practitioners pay visits at fixed hours on most working days of the week. Sports activities are a part and parcel of campus life and there are two badminton courts available for use by the research faculty, staff and students. Football is also a part of the daily routine for the members of the RRI community. Table tennis and cricket tournaments regularly organized at RRI also see healthy participation by students and members of the faculty and staff.

ACADEMIC PROGRAMMES

PhD Programme

RRI has a comprehensive PhD programme that gives enthusiastic and motivated students the opportunity to join the highly competitive global research community. The PhD programme is an organic process aimed at challenging graduate students to rise to their full creative potential and develop the ability to conduct independent research. RRI offers an exceedingly high degree of intellectual freedom to students allowing them to pursue their individual interests within the four broader areas of research conducted at the institute. This level of freedom coupled with proper guidance in the form of constant formal and informal interactions with faculty and other students encourages the students to not only think for themselves but also critically question others. A regular exchange of ideas and knowledge promotes an open-minded approach towards science and a willingness to learn which is, as acknowledged everywhere, extremely important for success in the academic arena. Apart from the academic members within the institute itself, graduate students under the PhD programme are also exposed to the larger and more diverse scientific community through attendance of relevant national and international conferences and workshops where they get a perspective on a bigger picture in their field of research.

Students at RRI are registered for their PhD degree with Jawaharlal Nehru University, New Delhi. RRI is also a participant in the Joint Astronomy Programme (JAP) with the Indian Institute of Science, Bangalore and the Physics and Biology programme with the National Centre for Biological Sciences, Bangalore. Further details on the PhD programme, admission requirements and procedure can be found on the institute website.

Currently 76 students from all over India are enrolled in the PhD programme and conducting research with faculty members from the four broad research groups at the Institute. Last year 9 PhD degrees were awarded and 9 were submitted for review.

Postdoctoral Fellowship Programme

RRI offers a postdoctoral fellowship programme, which is open for application through the year. This fellowship is initially offered for a period of two years and usually extended to three, following review. Postdoctoral fellows are expected to work independently and have complete academic freedom in the sense that they can choose their own research problem and collaborator. It is not mandatory that a post doctoral fellow works under the purview of any of the four broad research groups at RRI either or is attached to a specific research faculty at the Institute. However, it is desirable that their professional research interests and previous experience in research has a significant overlap with the ongoing and envisaged research plans of the institute. The reason is that RRI does not wish to have postdoctoral fellow working in isolation. Rather a healthy amount of mutually beneficial interaction with the faculty is desired so that collaborations can be struck up. Also participation of the fellows in the academic activities of the Institute and student supervision as co-guides is encouraged even though there are no teaching responsibilities.

Candidates who have at least one year of experience as a post doctoral researcher and have a proven tract record of being able to conduct original and independent research can apply for a limited number of Pancharatnam Fellowships offered at RRI. Here too, applications are accepted throughout the year and the processing takes about 4 to 6 months. The fellowship is for 3 years. Further details about the Postdoctoral and Pancharatnam Fellowships can be found on the RRI website (www.rri.res.in).

Currently, there are 13 postdoctoral and Pancharatnam fellows and one DST INSPIRE Facultyat RRI from the country and abroad.

Visiting Student Programme (VSP)

The Visiting Student Programme is aimed at offering research experience to highly motivated students pursuing Undergraduate or Master's studies student; sometimes accepted even exceptionally talented high-school students. The Visiting Students Programme runs throughout the year.

During the period of their visit, these students work closely with at least one staff member of the Institute on a suitable project, or on a part of a project, as appropriate. The student's work and the interaction with the staff and the PhD students at the Institute are expected to provide her/him a flavour of the research pursued here, in general, and a first-hand experience of research, in particular.

Available projects/mentors and relevant resources limit total number of visiting students at a time. During the year 2015-2016, a total of 122 students from different parts of the country participated in the programme, with the duration ranging anywhere between six weeks to six months.

PEOPLE AT RRI

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Soft Condensed Matter

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Research Interests: Electrochemistry
Email: jagadeeshrv@rri.res.in
Advisors: V Lakshminarayanan, Arun Roy

Sushil Dubey
Research Interests: Biophysics
E-mail: dubeys@rri.res.in
Advisor: Pramod Pullarkat

Meera Thomas
Research interests: X-ray studies on ionic amphiphile systems
E-mail: meerathomas@rri.res.in
Advisor: VA Raghunathan

Buti Suryabrahmam
Research Interests: Phase transitions of amphiphilic systems.
Email: suryabrahmam@rri.res.in
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Madhukar S
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Advisor: VA Raghunathan

Sanjay Kumar Behera
Research Interests: Glass transition and rheology of aging colloidal suspension
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Advisor: Ranjini Bandyopadhyay

Deepshika Malkar
Research Interests: Experimental soft condensed matter – bent core hockey stick liquid crystals
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Advisor: VA Raghunathan

Anindya Chowdhury
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Subhadip Ghosh
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Theoretical Physics

Chaitra Shreepad Hegde (upto 31.7.2015)
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Advisor: Abhishek Dhar

VV Prasad (upto 31.7.2015)
Research Interests: Statistical physics
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Advisor: Sanjib Sabhapandit

Suman Gaurab Das (upto 31.7.2015)
Research Interests: Energy transport in one-dimensional systems
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Advisor: Abhishek Dhar

Arnab Pal (upto 31.7.2015)
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Advisor: Sanjib Sabhapandit

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Advisors: Supurna Sinha, Joseph Samuel

Anirudh Reddy
Research Interests: Aspects of classical and quantum cloning
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Advisor: Supurna Sinha

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Advisor: Madan Rao

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Advisor: Madan Rao

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Advisor: Sanjib Sabhapandit

Amit Kumar
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Advisor: Madan Rao

Mriganko Mrinmoy Roy (upto 24.2.2016)
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Advisor: Sumati Surya

Santanu Das
Research Interests: Statistical mechanics
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Advisor: Sanjib Sabhapandit

Syed Nomaan Ahmed
Research Interests: Exploring particle propagation on sprinkled causal sets, a coordinate invariant vacuum called the Sorkin-Johnston vacuum
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Advisor: Sumati Surya

D. Abhishek (till 12.4.2016)
E-mail: abhisi@rri.res.in

Adit Raj Sharma
Research Interests: Gravity, statistical physics
E-mail: aditraj@rri.res.in

Alkesh Yadav
Research Interests: Biophysics. In particular - Eukaryoyic cells have anorganelle called Golgi complex. Golgi complex is a membraneous structure composed of several flattened sacs called cisternae. It is situated near the Endoplasmic Reticulum. The question being addressed is what sets the number of compartments in a golgi complex based on its functions.
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Advisor: Madan Rao

Visiting Scientists

Astronomy & Astrophysics

Subrahmanya CR
Jihad R Touma

Theoretical Physics

Abhishek Dhar
Anupam Kundu

Adjunct Professors

Muthukumar M
Barry Sanders
Shiv Visvanathan
Kandaswamy Subramanian
Satya Majumdar
Rafael Sorkin
Fabien Bretenaker

COUNCIL

Dr K Kasturirangan Chairman	Chancellor, Jawaharlal Nehru University New Mehrauli Road, New Delhi 110 067
Prof PK Kaw	Senior Professor & Distinguished Scientist Institute of Plasma Research, Gandhinagar 382 428
Prof. Ashutosh Sharma	Secretary, Department of Science & Technology Ministry of Science & Technology New Delhi 110 016
Prof Ravi Subrahmanyan	Director, Raman Research Institute Bangalore 560 080 (Ex-officio member)
Shri J.B.Mohapatra	Joint Secretary & Financial Advisor Ministry of Science & Technology Government of India, New Delhi 110 016
Prof AK Sood	Department of Physics Indian Institute of Science Bangalore 560012
Prof PC Agrawal (upto 31.7.2015)	DAE–UM (Dept. of Atomic Energy – Mumbai University) Centre for Excellence in Basic Sciences Mumbai University Campus at Vidhyanagari Health Center, Kalina, Santa Cruz (East) Mumbai – 400 098
Prof R. Rajaraman	Emeritus Professor, Theoretical Physics School of Physical Sciences, Jawaharlal Nehru University New Delhi 110 067
Prof. Vijay Bhatkar (from 1.8.2015)	Chairman, ETH Research Lab Bavdhan, Off Mumbai-Bangalore Bypass, Pune - 411 021

FINANCE COMMITTEE

Dr K Kasturirangan Chairman	Chancellor, Jawaharlal Nehru University New Mehrauli Road, New Delhi 110 067
Shri J.B. Mohapatra	Joint Secretary & Financial Advisor Ministry of Science & Technology Government of India, New Delhi 110 016
Prof. Ravi Subrahmanyan	Director, Raman Research Institute Bangalore 560 080
Prof R. Rajaraman	Emeritus Professor, Theoretical Physics School of Physical Sciences, Jawaharlal Nehru University New Delhi 110 067

Other Staff

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Administrative Officer
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C.S.R. Murthy (from 1.7.2015)
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GV Indira

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Light and Matter Physics

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Theoretical Physics

G Manjunatha
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RAL Lab

Mamatha Bai R
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Accounts

PV Subramanya, Accounts Officer (upto 30.4.2015)
Suresh Varadarajan, Accounts Officer (from 9.4.2015)
R Ramesh, Internal Auditor
V Raghunath
R Pradeep

Purchase

C N Ramamurthy, Purchase Officer
M Prema
G Gayathri

Stores

B Srinivasa Murthy, Stores Officer
MV Subramanyam (upto 31.8.2015)

Upkeep

Hanumantha
Jayamma
KN Kawalappa
C Lakshmamma
T Murali
Narayana
Sidde Gowda

V Venkatesh
Ramanna
Varalakshmi

Estates and Buildings

GB Suresh, Civil Engineer
R Sasidharan, Supervisor (upto 31.10.2015)
S Anantha Raman
K Bhoopalan
Gunashekar
C Haridas
KN Srinivas
K Palani
M Rajagopal
K G Narasimhalu
M Ramesh

Security

CN Ganapathy, Consultant (upto 31.10.2015)
BM Basavarajaiah
UA Earappa
H Gangaiah
Keshavamurthy
Suresha
K Krishnappa
K Pushparaj
OM Ramachandra
G Ramakrishna
M Sannaiah
H Vaderappa

E. Martin Dass (Consultant from 1.7.2015)

Transport

M Balarama
CK Mohanan
G Prakash
Rahamath Pasha
G Raja
M Venkateshappa

Amenities (Guest House & Hostels)

Srihari Prahlad, Canteen/Guest House Manager (upto 4.9.2015)
N Narayanappa, In-charge
Shivamallu
Mangala Singh
Muniratna
T Naganna
DB Padmavathy
PC Prabhakar
N Puttaswamy
A Raju (upto 31.1.2016)
Uma
Sharadamma
Yashodha

Horticulture

A Ramanna
Bylappa
Lingegowda
D Mahalinga
Mailarappa
Marappa
D Muniraja
S Muniraju
Rangalakshmi
D Krishna
T. Mahadeva

Medical

Consultant Paediatrician: Dr MR Baliga
Consultant Physician: Dr BV Sanjay Rao
Consultant: Dr. P.H.Prasad
Technician: R Shanthamma

Carpentry

M Gopinath

Gauribidanur Telescope

Support Staff

Bheema Naik
Gangaram
Papanna
RP Ramji Naik
Ranoji Rao (upto 31.5.2015)
Shivarudraradhya (upto 29.2.2016)
Venkataswamy
NR Srinath

PUBLICATIONS

Members and students of the Raman Research Institute publish their research activities carried out over the year in several national and international peer-reviewed journals. Each of the four research groups at RRI publishes their work in renowned journals that focus on their specific research area.

For the Astronomy and Astrophysics group, these include, but are not limited to, the Monthly Notices of the Royal Astronomical Society, Astrophysical Journal, Astrophysical Journal Letters, Astronomical Journal, Annals of Physics, Experimental Astronomy, Research in Astronomy and Astrophysics, Astronomy and Astrophysics, Experimental Astronomy, Journal of Cosmology and Astroparticle Physics, IEEE Transactions on Antennas and Propagation, Publications of the Astronomical Society of Australia and others.

The Soft Condensed Matter group at RRI has its work published in journals like Liquid Crystals, Langmuir, Soft matter, Proceedings of the National Academy of Sciences, Physical Review, Review of Scientific Instruments, Journal of Physics: Condensed Matter, AIP advances, Biophysical Journal, PLOS One, RSC Advances, Journal of Applied Physics, Current Science, Pramana, Chemical Communications, Journal of Colloid and Interface Science, Journal of Chemical Physics, Physics and Chemistry of Liquids, Physical Chemistry Chemical Physics and many more.

Publications of the Light and Matter Physics group can be found in Physical Review, Applied Physics, Journal of Optical Society of America, Applied Optics, Applied Physics Letters, Journal of Applied Physics, Nanotechnology, Nano letters, Nanoscale, Optics Letters, European Physical Journal, Journal of Alloys and Compounds, Journal of High Energy Physics, Journal of Materials Chemistry, Materials Chemistry and Physics, Optical Materials, Plasmonics, Physics of Plasmas, Bulletin of Indian Laser Association, Superconductor Science and Technology, Chemical Physics Letters etc.

Theoretical physicists at RRI use journals like Physical Review, Physical Review Letters, Review of Modern Physics, Proceedings of the National Academy of Sciences, Journal of Physics: Condensed Matter, Classical and Quantum Gravity, Europhysics Letters, Journal of Statistical Mechanics, Current Opinion in Cell Biology, Journal of Physical Chemistry and others as a medium to share their knowledge with the national and international scientific community.

140 papers with RRI members as authors and/or co-authors were published during 2015-2016. There were 15 publications in conference proceedings and 27 publications (26 in journals and 1 in conference proceedings) are in press.

Members of the Institute also regularly publish books and/or articles for popular science magazines to reach out to a wider audience beyond that of specialized technical and scientific journals. RRI members published 1 book chapter/review and in the past year and 3 popular science articles.

A full list of publications by each of the institute members is provided in Appendix I.

OTHER ACTIVITIES

Conferences

Institute members frequently visit various other institutions both abroad and at home to attend conferences and workshops. These events play an important role in providing an opportunity to exchange ideas with the scientific community at large and thus set the stage for future collaborations with researchers from other institutions, both within India and abroad. Last year, faculty and students of the Institute attended numerous conferences in India, USA, Australia, Japan, Singapore, UK, Spain, Colombia, Italy, Germany, France, Switzerland, Hungary, Malaysia and Canada.

In addition, faculty members gave lectures and invited talks at a variety of workshops, international conferences, multinational project meetings and training programmes. As a part of the outreach activities of RRI, members also visited colleges around the country and organized special workshops on different research topics, delivering lectures, talks and presentations.

A full list of conferences attended by the Institute members is available in Appendix II.

Seminars and colloquia

Seminars are regularly organized at the Institute to keep all members abreast of the latest, cutting-edge research being done on specific research topics. They are delivered by visiting faculty and researchers from other institutions and are intended to generate discussions on topics that are of particular interest to RRI members and also constitute collaborative projects between RRI and the visitor's institution.

The Thursday colloquium is a novel event held at the Institute to promote further interaction not only between the various research groups within RRI but also between RRI and the invited speaker and his or her affiliated institution. However, unlike the seminars, the topics covered at the colloquia do not strictly adhere to current research being pursued at RRI. The colloquium aims to cover new science topics and bring an interdisciplinary flavor to the event by introducing themes from various other disciplines to the members of the RRI community.

During the last year, RRI invited speakers from all over the globe to deliver the Thursday colloquia. The topics covered a lot of diverse themes including "Global and national perspectives on Lead poisoning", "Active mechanics and dynamics of epithelia during morphogenesis", "Quantum communication networks", "K.S. Krishnan: His life and work", "Black holes and neutron stars in our galaxy as laboratories for strong gravity", "Drops behaving badly", "Self-assembly of colloidal rafts", "Trees of Bangalore", "A journey from astronomy to vision science" "Diffusion with stochastic resetting", "Gandhi's India: Gandhi Memorial Lecture" and many more.

A full list of seminars and colloquia held at the Institute is available in Appendix III.

Visiting Scholars

The Institute recognizes that it is imperative to stay nationally and internationally open and foster an environment that allows for greater exchange of ideas and more collaboration. With an aim to further augment the interaction between the members of the Institute and scholars belonging to other institutions, RRI actively encourages visits from a large number of scientists, researchers and engineers. These scholars visit the institute and contribute new ideas and skills while also benefiting from the expertise of RRI's own members. Visits at RRI can last from a few days to a few months and often lead to fruitful collaborations and conceptualization of new, interesting projects for the Institute.

Last year there were altogether 106 scholars who visited RRI from both Indian and international institutions. RRI is happy to have so many friends and thanks all of them for contributing to the wonderful diversity and dynamism of the research atmosphere at the institute.

A list of all visitors, where they came from and when they visited RRI can be found in Appendix IV.

Science Forum

Owing to the very large number of papers that are published annually, these days it is nearly impossible for a scientist to stay abreast of the research going on outside his or her areas of specialization. To partially remedy this situation, the RRI Science Forum was conceptualized and first came into being in 2014 at RRI. The goal was to provide an attractive forum to all academic members on campus for discussions on current research in a variety of topics. The organizers of this regular event are Gautam Soni, Andal Narayanan & Nayantara Gupta. The RRI Science Forum is now held once in 2 weeks on Thursdays between 3:30-4:30pm.

Talks at this forum comprise of 2 parts, the first introductory talk of about 20 minutes (where the field is introduced to non-experts at a very basic level by a faculty member or postdoctoral fellow) followed by the "Science Talk" (where the chosen paper is presented by a PhD student).

Typically, as a part of the RRI Science Forum meeting, papers with exciting new results that are often considered landmarks in that particular field are presented to a wider and more general audience. Based on the presentation, informal discussions, questions and demonstrations are strongly encouraged leading to a better understanding of the underlying concepts of the work presented. This in turn often results in new ideas and new research problems for the members of the RRI scientific community to work on.

being Nayantara Gupta and Jagdish Joshi. Through the year 2015-2016, RSF has become a great platform to learn about and appreciate the breadth of research done in RRI.

A list of the papers reviewed during the RRI Science Forum meetings last year is attached to the annual report as Appendix V.

PhD awarded

Santosh Prasad Gupta: Studies on novel phase behavior of ionic amphiphile-water systems

Rajib Basak: Dynamic light scattering and rheological studies of some micellar copolymer solutions, biopolymer gels and concentrated colloidal suspension
Seshagiri Rao: An optical fibre based force apparatus: applications to soft and living matter

Anagha Datar: Mechanisms of shape transformation and retraction in axons

Tridib Ray: Progression towards study of interactions with composite systems at ultra-cold temperature

Jayakumar A: Interplay between shape, order, and topological defects: Elasticity of some softmatter systems

Anjan Roy: Understanding diffusion through microscopic models

Arnab Pal: Understanding fluctuations in no-equilibrium systems

Debasish Saha**:** Experimental studies of the dynamics and flow behaviors of colloidalnanoclay glasses andgels

PhD submitted

Anu Renjith: Electrochemical studies in soft ionically conducting medium - Deep eutectic solvents and ionic gels

Avinash BS: Synthesis, characterization and properties of some novel discotic nanocomposites

Chaitra Shreepad Hegde: Tagged particle diffusion in one dimensional to chastic systems

Samim Ali: Experimental investigations of dispersibility, stability and rheological behaviors of aqueous suspensions of colloidal clays

Jagdish Chandra Joshi: Gamma rays, neutrinos & antiprotons from interactions of cosmic rays

Prasad VV: Driven inelastic gases

Jyothi S: Exploring molecular ion formation, trapping and detection in hybrid system

Renu Vishavkarma: A study of cell adhesion and mechanosensitivity

Suman Gaurab Das: Energy transport and relaxation in one-dimensional Hamiltonian systems

General

The following grants were received from the Department of Science and Technology during the year:

		Amount in lakhs – rupees
PLAN	Recurring and non-recurring	3,477.00
NON-PLAN	Recurring	50.00
Total:		**3,527.00**

Official Language Activities

During 2015-16, under its Annual Programme, RRI has strived to achieve all targets prescribed by the Government of India. The Institute has taken several important steps for OL implementation and its betterment. RRI's official language implementation committee, in brief called ROLIC has made noteworthy progress in re-orienting Hindi workshops towards enhancing usage of Hindi in the day-to-day work of employees. Workshops concentrated on making the official language user-friendly.

ROLIC was reconstituted during 2015 to include representatives from all research and administrative groups of the Institute. To adhere to the OL Act, Rule & Policy related provisions, periodical checks were introduced and further improvement in the OL implementation of the Institute is expected.

The Institute has organized workshops for its employees quarterly during 2015-16. Details are listed below. Additionally, the Institute has conducted competitions for employees to promote OL and has rewarded deserving employees. Hindi Fortnight and Hindi Day were celebrated during 14–28 Sept 2015 in which many competitions in Hindi were held. A written quiz too was conducted on 18th March 2016. The participation of the employees was reassuring. These programmes, like in previous years, were jointly organized and sponsored with Indian Academy of Sciences which is co-located.

Hindi workshops

Sl. No.	Date	Topic of the workshop	Lecture by
1.	12 June, 2015	How to use Hindi on Computer?	Anand OL Officer HAL Engine Division, Bengaluru
2.	18 September 2015	Bharatiya Sahitya ke nirman main Hindi	TG Prabhashankar Bangalore University, Bengaluru
3.	28 September, 2015	Special Lecture on Official Language Act, Rules and Policy	Narayana Singh Joint Director Central Translation Bureau Bengaluru
4.	18 December, 2015	Practical issues of Official Language implementation and suggestions	Malatesh Mailar Sr Translator Microwave Tube Research and Development, DRDO, Bengaluru
5.	29 March, 2016	Functional Hindi & Translation in the perspective of Official Language	Pratibha R Mudliar Chairperson Department of Studies and Research in Hindi, Mysore University, Mysore

Reservations

The institute follows the same reservation policy as other Government of India scientific departments.

Others

During the period 2015-16, the RRI community has organized several special conferences, meetings and workshops described in detail in the next section titled 'Events organized during 2015-2016'. Other annual events and activities at RRI include in-house meetings, high teas on superannuation for faculty and administration, welcome address for the new joining batch of PhD students, college visits, and invitation of college students to the campus. Formal and informal dinners and high teas, sports tournaments, concerts, and a variety of cultural programmes, both with invited performers and RRI members themselves, are regular features at the RRI campus.

Public Outreach

The word 'outreach' is defined in the English dictionary as the act of reaching out. An 'outreach program' conducted by scientists is therefore a way for the scientific community to create contact with the world outside of science. As researchers working at the frontier of new and exciting science, we automatically enjoy the privilege of easy access to knowledge, not only limited to our own work but also that of the entire world. But this behooves upon us the responsibility to create for society future pioneers who can carry the torch forward. Outreach is the only mode to bridge this gap between those who 'do science' and those who 'do not'. Some RRI members, students and faculty, have been rather active in this sphere during the past six months.

Ajay Kumar, PhD student, LAMP, is a regular volunteer at the Notebook Drive (NBD) at IISc. NBD started in 2002 as a scheme to distribute notebooks to underprivileged students at one government school. Today, NBD has grown to encompass over 21 primary schools, 5 high schools, more than 100 teachers and 3000 students. Among other things, its activities include teaching science, English and computer science through weekly sessions. Ajay is part of the English-teaching group, and you can find him conducting English classes at schools every Saturday.

Gayathri Raman, PhD student, A&A and Mayuri S, Research Associate, A & A are also NBD volunteers at their science outreach sessions and also their mentorship programs. Another outreach group called the Masti Ki Prayogshaala (MKP) that is operating in multiple states of the country has recently developed a Bangalore chapter. MKP-Bangalore visits nearby local schools and conducts science outreach sessions. Gayathri participated in the recently held Astronomy outreach session conducted at a school in Kundalapalli by MKP-Bangalore.

Mayuri is a regular at the NBD mentoring sessions held at IISc every Sunday, where she enjoys demonstrating simple science experiments. Based on the 'Toys from Trash' philosophy of Arvind Gupta Toys, the experiments and models use simple daily commodities and can be performed and operated by the primary and high school students themselves. Additionally, Mayuri is a founding member of HOLI – Hands on Learning Initiative, which aims to promote a hands-on approach to learning. HOLI currently goes out to schools and communities in and around Pune and Bangalore, conducting workshops and 'Experiential exploratory' sessions with its sister organization DLRC – Drive Change and Learning Resource Center (Pune).

The Electronics and Engineering Group, EEG, RRI in association with the Department of Physics & Electronics, Christ University, Bangalore, organized a one-day workshop on a very interesting topic - **"Engineering contribution to the advancement of Modern Science"** on 30th January 2016 at the Christ University campus. This event was a part of the RRI outreach program. Besides talks the workshop also included a session dedicated to experiments to promote real hands-on learning. The RRI academic faculty who participated in the workshop included the Director and B. Ramesh, along with four EEG members – A. Raghunathan, Somshekar, Girish and Srivani. The emphasis of the talks was on radio telescopes, antennas and radio receivers – their designs and applications and inherent engineering challenges, with talks such as, "Engineering for visions of the cosmos", "Telescopes, the Artificial Eyes" and "Importance of Digital Logic Design using FPGA-based Systems".

The Light and Matter Physics Group along with the Department of Physics, St. Joseph's College and friends organized a two-day workshop on **"Modern Optics"** on February 8th and 9th, 2016 at the St. Joseph's College campus in Bangalore. The target audience comprised 89 students at both undergraduate (31 percent) and Master's level (61 percent) and college faculty (8 percent). Close on the heels of the Christ University workshop (see above), this was another excellent initiative to reach out and communicate our research to the general public and motivate younger minds to take up a research career.

The talks addressed a wide variety of topics broadly under the purview of modern optics with titles "Fourier Optics", "Fourier Optics and Astronomical Imaging", "How glass enhances our vision of the Universe", "Ultrafast Lasers and nonlinear optics", "Quantum features of light" and "Quantum leaps in precision measurements." Speakers included Reji Philip, Andal Narayanan, N.V. Madhusudana and Udaya N. Shankar of RRI and Rajaram Nityananda (Azim Premji University), A.R. Usha Devi (Bangalore University).

As conveners of the workshop, Reji and Andal have recorded feedback from the attendees on the usefulness of the workshop and the brief survey met with

overwhelming success. It can be fairly summed up by the fact that 94 percent of the attendees expressed interest in participating in such a workshop in future as well.

A Scientist at a Holistic-Science Workshop

On 4th January 2016, I attended one day of a 4-day workshop on "Understanding Holistic Science and Complexity" conducted at Bhoomi College, Bangalore. The workshop aimed to “review one's thinking process which has been deeply influenced by linear and reductionist thinking".

The principal speaker, Philip Franses, a Holistic Science Faculty at Schumacher College, UK, who initiated the discussions, attempted to find hidden truths in physical principles and mathematical formulations of classical and quantum physics. These truths, apparently, are able to answer questions best described as anthropocentric philosophical musings. I was initially appreciative of the intent of the workshop in finding solutions to the myriad environmental crises we face today through “exploration of connections beyond isolated entities". However, my own understanding of the talks and discussions was that the whole exercise was ambiguous at its best moments and unfortunately, factually incorrect at its worst. However a majority of the audience who were from a general non-science background thought otherwise. This whole experience revealed the necessity for practicing scientists to engage with the general public and convey the wonder and joy in knowing science for science's sake. It is important to demystify science and make it accessible to the general public while hoping that the curious amongst them will engage with an open mind and go on to acquire tools which will better their understanding.

However, as important as it is to demystify science, it is equally important to understand and convey its limitations. On a personal note it is quite disturbing that in a country with such a rich philosophical heritage, people should find the need to relate their own philosophical queries to the inherently non-intuitive interpretations of Quantum Physics! It is a testimony to the fact that we need honest, committed and in-depth engagement to understand and develop a skill in anything--be it in science or in philosophy. Approximated and superficial rendering of truths can only go so far and like a movie trailer, will tantalize in its limited-time edition but can end up being profoundly disappointing in its final appeal.

Andal Narayanan
Associate Professor, Light and Matter Physics Group

EVENTS AT RRI

Visit to Raman Research Institute by the Hon'ble Union Minister of Science and Technology and Earth Sciences, Dr. Harsh Vardhan, on 21st August 2015

The Honorable Minister was welcomed to the Institute by the Director, given presentations and tours to give first hand experience of the value and standing of the research efforts in the national and international context, particularly in-house development of experiment based research that continues the unique spirit and passion of the Founder, Sir C V Raman.

The Honorable Union Minister walked on an exploration of the campus via tree-lined paths, through corridors and laboratories, to interact directly with staffs and students, understanding (a) RRI participation in international partnerships with precursor Radio Telescopes in the lead up to the International Square Kilometre Array (SKA), which is a designated mega project of the nation, (b) RRI efforts in building in-house the science payload for an Indian X-ray polarimeter satellite mission – XPoSat – in project mode with ISRO, which will be the first dedicated X-ray polarimetry mission of the world ahead of any NASA and ESA space missions in this field of research, (c) Participation of RRI in ASTROSAT, India's first space astronomy satellite, (d) RRI cluster of Quantum optics laboratories, which are now established as a leading center for cold-atom and quantum information research in the country, (e) RRI cluster of soft matter and biophysics laboratories leading research on materials and cell structure dynamics, and (f) the radio astronomy laboratory at RRI that builds precision radiometers for detection of spectral distortions in relic cosmic radiation from the early evolution of the Universe.

The candid and forthright interactive sessions of the Honorable Union Minister with the students and staff proved exceedingly motivating and encouraging. He inspired the students with his account of courageous undertaking of the challenge of eradicating polio from the country, inspired the scientific staff to follow in the path of the stellar physicist and Nobel Laureate Sir C V Raman, and "Dream big for Science and for Society".













Annual RRI In-house Meeting, 2015

The RRI In-house meeting was held this year during April 15th-17th at the Main Building Auditorium, a trifle late compared to other years, but to great success nevertheless. The In-house meeting is primarily a platform to bring together the whole academic community in RRI, students, faculty as well as support staff and give them an opportunity to present their work through poster and oral presentations and get acquainted with the ongoing research in the institute in laboratories/groups apart from their own. This year's In-house was no exception, as was evident from the level of participation in the meeting.

This year, speakers from across the four research groups and facilities like the Library and the Radio Astronomy Lab gave oral presentations of twenty minutes each through the three days of the event. As many as thirty speakers took to the podium and presented their work.

There was also a poster viewing session on the first two days of the meeting with eight participants having submitted their abstracts for poster presentation.

The last event on the schedule was an hour-long open house discussion on the 'Five year limit of PhD Programme at RRI and No Stipend-No Accommodation Policy ', chaired by Ranjini Bandyopadhyay.

As has been the norm during previous annual In-house meetings, this year too the meeting concluded with a cultural evening followed by dinner at the Library Block Terrace. Students, faculty as well as their families took to the stage to display their talents in music, dance, etc. T-shirts designed by the organizing committee customized by the RRI logo were also distributed at the event.

The organizing committee for the In-house 2015 comprised of the entire batch of third-year PhD students. The names of staff and students who gave talks and the titles of their presentations can be found at http://rri.res.in/~inhouse/schedule.pdf



Poster presentation in progress





Cultural performance at the Inhouse 2015

Indian Cell Mechanics Meeting, 2015

As part of the second workshop on "Mechanical Manipulations and Responses at the Scale of the Cell and Beyond", RRI in collaboration with National Centre for Biological Sciences (NCBS), and International Centre for Theoretical Sciences (ICTS, TIFR), organized the Indian Cell Mechanics Meeting, 2015 at the RRI Main Building Auditorium during April 24-26.

The understanding of biological processes at a cellular and sub-cellular scale has made a big leap forward, thanks to the availability of new microscopy tools that enable sub-diffraction resolution and high-speed live cell/tissue imaging technologies. Recently, the application of a wide variety of techniques to mechanically manipulate single molecules or multi-cellular cell composites has allowed scientists to begin addressing the question of how organisms react to controlled mechanical cues. This three-day discussion meeting through its focused sessions on "Mechanics at the Molecular Scale", "Mechanics at the Cellular Scale –

i) Cytoskeleton and
ii) Membrane" and "Mechanics at the Organism Scale" allowed for intensive discussions on problems that aim at garnering quantitative information on the responses of biological material (at all scales) to perturbations of a mechanical nature, and systematically deciphering the physics of how living material engages with mechanical information, through both experiments and theoretical modeling.

Attended by invited keynote speakers, G.V. Shivashankar (Mechanobiology Institute, Singapore), Pere Roca-Cusachs (University of Barcelona), Satyajit Mayor (NCBS, Bangalore) and around hundred members of the Indian Cell Mechanics community as well as some researchers from abroad, the event was a grand success. Participants presented their current research in this field and discussed future research opportunities in interesting topics in conference mode. Local participants who spoke at the meeting included Gautam Soni who delivered a talk on "Nanopore Biophysics: From molecular detection to Biology" and Madan Rao, whose talk was titled "Actomyosin Pulsation and Symmetry Breaking flows drive Tissue Remodeling".

A highlight of the meeting was the presentation by the University of Minnesota based Black Label Movement (BLM), titled 'Bodystorm hits Bangalore' held at the National Gallery of Modern Art (NGMA), Bangalore on 26th April. A collaborative project by biomedical engineer, David Odde and dancer/choreographer, Carl Flink, the presentation featured dancers from BLM and eight selected dancers from India. Bodystorm is a concept where choreographed dance movements are used to represent physics-related questions in biological problems. The fundamental idea behind it is to use simple interaction rules that dancers, as an assembly, follow on stage, to simulate and understand biological processes.



Cosmology with the HI-21cm Line

The Indian Cell Mechanics Meeting in April was followed by a national workshop on "Cosmology with the HI 21-cm line" organised on campus during June 23-26. The National Centre of Radio Astrophysics (NCRA), Pune and the Raman Research Institute (RRI), Bangalore were the joint organizers.

The 21-cm line of neutral hydrogen (HI) is a promising tool for studying the evolution of the universe, from the dark ages to the present epoch. A number of groups within India and worldwide are working on both theoretical and observational aspects of cosmology with the HI-21-cm line.

In keeping with Indian participation in ongoing and upcoming experiments involving 21cm cosmology, which include GMRT, OWFA, SARAS, MWA and SKA, the workshop focused on a detailed exchange of information on the ongoing research work in various institutes and encouraging fresh graduate students to embark on research in this exciting field.

Keynote addresses, invited reviews and contributed talks were on:

- The cosmological 21-cm signal
- Detection of the signal using precision receivers
- Foregrounds
- Cross-correlations with other cosmological signals
- Specific instruments: GMRT, OWFA, SARAS, MWA, SKA
- HI in the ISM of galaxies
- Studies of individual systems

The invited review talks were delivered by Avinash Deshpande (RRI), Jasjeet Bagla (IISER, Mohali), Jayaram Chengalur (NCRA), Nissim Kanekar (NCRA), Ravi Subrahmanyan (RRI), Saiyad Ali (Jadavpur Univ.), Shiv Sethi (RRI), Somnath Bharadwaj (IIT Kharagpur), Srianand R. (IUCAA), Tirthankar Roy Choudhury (NCRA) and Udaya Shankar N. (RRI)

About forty participants, mostly graduate students and postdoctoral fellows, had the opportunity to hear about innovative research programs, share ideas, and network with colleagues working in complementary fields. The panel discussion in the program further facilitated this process.

Bangalore School on Statistical Physics - VI

The event schedule at RRI during April – September 2015 has been a really busy one! The Cosmology workshop in late June was immediately followed by the "Bangalore School on Statistical Physics – VI" held during July 02 – July 18th at the Main Building Auditorium.

This advanced-level pedagogical school was second in the series of such schools concentrating on Statistical Physics, being jointly organized by RRI and ICTS, following the highly successful first joint school. The present series is an offshoot of an earlier series of schools titled RRI School on Statistical Physics started in 2010 at the Raman Research Institute.

As in previous years, the school covered a wide range of topics of pivotal importance to modern day research in the field of statistical physics. Instructors covered not only well-established theories but also cutting-edge research topics through teaching modules and tutorials over the course of two weeks.

The courses offered were –

1. Introductory lectures on statistical physics - Abhishek Dhar (ICTS) and Sanjib Sabhapandit (RRI)
2. Introduction to soft matter physics – D. Pine (NewYork)
3. Directed percolation and Sandpile models – D. Dhar (TIFR)
4. Statistical Mechanics of Systems with Long-Range Interactions - D. Mukamel (Weizmann Institute)
5. Interacting particle systems - M. Barma (TIFR)
6. Physics of Molecular Motors - D. Chowdhury (IITK)
7. Large deviation functions and fluctuation relations in nonequilibrium systems - S. Sasa (Kyoto)

Interacting with a few participants of the school, it was easy to make out that D. Dhar and M. Barma from TIFR were the crowd favourites so far as the theory courses were concerned, while Mukamel and Sasa's modules were of special interest to those researchers who work on numerical simulations. A flavor of biological physics was introduced by Debashish Chowdhury's lectures while David Pine told us about the many mysteries in the world of colloids, surfactants and other soft matter.

New Colloids Discussion Meeting, 2015

Timed to coincide with David Pine's (New York University) visit to Bangalore, RRI hosted a fourth meeting on campus in the early half of 2015, the New Colloids Discussion Meeting, 2015. The meeting held during July 19-21 proposed to encourage discussion between physicists, chemists and engineers on the many exciting new areas of soft matter research, especially but not limited to, colloids.

David Pine himself delivered three keynote lectures spread out over the three days of the meeting, on "DNA coated colloids with and without directional interactions", "Random Organization: Reversibility in non-Brownian suspensions" and "Colloidal surfers". The other invited

speakers at the meeting were from IISc, JNCASR, IISER Kolkata, NCL Pune, IISER Bhopal and University of Hyderabad. Some of the topics of the invited talks, among many others, were –

- Macro-assemblies from bonding colloids
- Biomimetic behavior of synthetic particles
- Structural glass transition in new colloids
- Dilute (anisotropic) suspension rheology
- Magnetic nano-swimmers
- Liquid Crystal colloids and their structural transition
- Flow-induced self-assembly and propulsion in active colloids.

Poster presentation was also a part of the program.

Meant to be a small, informal meeting, there were about twenty-five participants, students and postdoctoral fellows, apart from the invited speakers this year, including five students from RRI. The meeting, especially the second day's program was met with much enthusiasm by the participants. The success of the meeting has resulted in discussions for a proposal to have an annual discussion meeting on soft matter research in Bangalore.

A Cultural Evening

On 4th September, we invited 'Stagecraft', the theatre wing of the NCBS Cultural club to stage an original play of their choice at RRI at the Library block terrace. The audience consisted of members of the RRI community, and their families and guests.

Composed of students from the National Centre for Biological Sciences (NCBS) and the Indian Institute of Science (IISc), 'Stagecraft' explores the art of theatre through various perspectives and styles in this debut anthology of plays.

On the evening of 4th September, 'Stagecraft' presented on campus 'V' - an evening of five original short plays, Paradise, The Mooneater, Birds and Other Carnivores, Paper on the nose and Phoren.The pieces spanned different genres of the theatrical palette ranging from physical theatre to absurd tragicomedy toa musical. 'Five' had premiered at NCBS on 17th July and this was their second performance. The run time of the event was approximately sixtyminutes without any intermission.

A video of the event as well as still photographs was shot by our in-house photographer and a few students. The play was followed by dinner at the same venue 7:30p.m onwards. Play and dinner both, were open to all, friends and family included.

The event was very well received and a good time was had by all, thanks in no small measure to the dedication of a group of individuals on campus who worked hard to put the show together, starting from erectingthe stage, the light and soundsystem, arranging the props, catering, etc. Stagecraft themselves went on to enact the very same set of plays the following day, i.e. on the 5th, at an annual theatre festival conducted by the National Law School, called Admit One.

The happy aftermath of 4th September has been the coming together of a motley group of students to try and launch our very own Music Club and Theatre Club. Efforts are also on to put our student community in greater touch with students at IISc and NCBS especially where cultural pursuits are concerned. We are all looking forward to another such evening where our own in-house artists will treat us to a performance.





Prabahan Chakraborty, Director of V, NCBS



Birds and other Carnivores



Paradise



Moon-eater



Paper On the Nose



Phoren

Other Events

The **Bangalore Environment Trust organized a half-day long seminar** at the Main Auditorium in RRI on 7th November 2015 through morning until lunch hour. Bangalore as we are all aware was once called the "Garden City of India" for its rich greenery. In that same city, it is now a common practice to fell trees indiscriminately on grounds of road-widening, construction and 'infrastructure' enhancement. The Karnataka Preservation of Trees Act of 1976, although a far-sighted legislation for its time, has not helped in preserving the greenery of Bangalore city, nor of the other urban areas of Karnataka. Amendments to the Act, including one issued on 13 January 2015, have made the situation worse. The amendment recently, expanded the list of trees that can be felled without permission to 27. It also increased the number of trees that can be cut in public interest and for domestic purposes.

The seminar organized by the Bangalore Environment Trust (BET) was meant to highlight the shortcomings of the Tree Act in its current form, the way it is being implemented in urban areas and suggest ways to move forward with urbanization while preserving our precious green cover.

February 28 is celebrated nationwide as the **National Science Day**, in order to commemorate the discovery of Raman effect in India by RRI founder, Sir C.V. Raman on the same day in the year 1928. This year, National Science Day was observed in RRI with a special outreach program involving school and college students from Tumkur, Mysore as well as Malleswaram and Rajajinagar areas of Bangalore. The program was organized in association with Breakthrough Science Studies, Bangalore (BSS). BSS had arranged for a "Science March" for the students from IISc to RRI on the morning of that day. Upon their arrival, Shiv Sethi (RRI) addressed them and spoke about Raman's contributions to science, while Dr. K N Rajani (Treasurer, BSS) highlighted the importance of scientific temper among students and in society, especially considering the challenges we are facing in current times. The event ended with the students being shown around the RRI Museum.

A workshop on **"Quantum Measure and Causal Set Theory"** was organized at the RRI Library block lecture hall by Sumati Surya during 4th – 8th January, 2016. This workshop was primarily meant to be an intensive discussion meeting where a few scientists from all over the world would exchange the latest developments and ideas in the field of Quantum Measure Theory and Causal Set Quantum Gravity.

The participants included Prof. Fay Dowker, Imperial College, London, Prof. Rafael Sorkin, Perimeter Institute for Theoretical Physics, Waterloo, Canada, Dr. Lisa Glaser, University of Nottingham, UK, Dr. David Rideout, UC San Diego, USA, and Dr. Petros Wallden, University of Edinburgh, UK along with several graduate students as well as faculty members of the TP group at RRI.

During the five days of the meeting, there were talks interspersed with detailed discussions. These were followed by separate discussion sessions at the end of the day on the topics of the day. The topics when broadly classified, explored four specific areas –

(i) The Quantum Measure Approach
(ii) The Sorkin-Johnston Vacuum
(iii) The Cosmological Constant and
(iv) Numerical Methods in Causal Set Theory.

This meeting was the second of such discussion meetings at RRI, the first being on the Quantum Measure held in January 2015. It was a thoroughly enriching experience for the Causal Set theorists among us and we hope this follow-up to the discussion meeting on Quantum Measure last year becomes an annual tradition in time.

A **review meeting** headed by the Chairman, **Karnataka Jnana Aayoga (KJA) or Karnataka Knowledge Commission,** Dr. K. Kasturi Rangan, to review the draft of the **Karnataka State Education Policy report** was held on February 1, 2016 at RRI.

It is well-acknowledged that Karnataka is fast emerging as a Knowledge State in the country and needs to take on the 21stcentury global challenges in terms of innovation, conservation of heritage, generation of new knowledge, skill development and application of knowledge in all spheres of life as a responsible global citizen, thus creating a more humane and evolved society.

To give a brief introduction to KJA – KJA is a body of experts constituted by the Government of Karnataka to help make recommendations for policy decisions. The reason for having a body like KJA in the state is mainly to engage experts in different areas and to obtain professional and knowledge recommendations for improving governance in state, translating into benefits for society and enabling the citizens of Karnataka.

At the 1st February meeting, recommendations were made to the Government on policy formulations to address problems in school-level education, teachers and faculty orientation, uniform systems of education and removal of disparities, governance structures for education management in future etc.

PUBLICATIONS

Papers in Journals

1. A search for fast radio bursts at low frequencies with Murchison widefield array high time resolution imaging
Tingay SJ*; Trott CM*; Deshpande AA; Prabhu T; Udaya, Shankar N; Srivani KS; Subrahmanyan, Ravi; +15 Co-authors
Astronomical Journal **150**, 199, 2015

2. Arp 65 interaction debris: massive HI displacement and star formation
Sengupta C*; Scott TC*; Paudel S*; Saikia DJ*; Dwarakanath KS; Sohn BW*
Astronomy and Astrophysics **584**, A114, 2015

3. Cosmic ray antiprotons from nearby cosmic accelerators
Joshi, Jagdish C; Gupta, Nayantara
Astroparticle Physics **65**, 108-110, 2015

4. Very high energy neutrinos from photo-disintegration of cosmic ray nuclei
Gupta, Nayantara
Astroparticle Physics **74**, 1, 2016

5. Proton Synchrotron Radiation from Extended Jets of PKS 0637-752 and 3C 273
Bhattacharyya, Wrijupan ; Gupta, Nayantara
Astrophysical Journal **817**, 6, 2016

6. Foregrounds in wide-field redshifted 21 cm power spectra
Thyagarajan N*; Paul, Sourabh; Prabhu T; Udayashankar N; Sethi SK; Srivani KS; Subrahmanyan, Ravi; +25 Co-authors
Astrophysical Journal **804**, 14, 2015

7. Numerical studies of dynamo action in a turbulent shear flow. I.
Singh, Nishant K; Jingade, Naveen*
Astrophysical Journal **806**, 118, 2015

8. Broadband spectral modeling of the extreme gigahertz-peaked spectrum radio source pks b0008-421
Callingham JR*; Deshpande AA; Prabhu T; Srivani KS; Subrahmanyan, Ravi; Udaya Shankar N; +22 Co-authors
Astrophysical Journal **809**, 168, 2015

9. Simultaneous observations of giant pulses from the crab pulsar, with the Murchison widefield array and parkes radio telescope: implications for the giant pulse emission mechanism
Oronsaye SL*; Deshpande AA; Prabhu T; Udaya Shankar N; Srivani KS; Subrahmanyan, Ravi; + 22 Co-authors
Astrophysical Journal **809**, 51, 2015

10. On the detection of spectral ripples from the recombination epoch
Sathyanarayana Rao, Mayuri; Subrahmanyan, Ravi; Udaya Shankar N; Chluba, Jens*
Astrophysical Journal **810**, 3, 2015

11. Discovery of low DM fast radio transients: Geminga pulsar caught in the act
Mann, Yogesh
Astrophysical Journal **815**, 126, 2015

12. On the detection of global 21-cm signal from reionization using interferometers
Singh, Saurabh; Subrahmanyan, Ravi; Udaya Shankar N; Raghunathan A
Astrophysical Journal **815**, 88, 2015

13. Chips: the cosmological HI power spectrum estimator
Trott CM*; Pjindor B*; Prabhu T; Udaya Shankar N; Sethi SK; Srivani KS; Subrahmanyan, Ravi; +45 Co-authors
Astrophysical Journal **818**, 139, 2016

14. The importance of wide-field foreground removal for 21 cm cosmology: A demonstration with early MWA epoch of reionization observation
Pober JC*; Hazelton BJ*; Deshpande AA; Prabhu T; Sethi SK; Udaya Shankar N
Astrophysical Journal **819**, 8, 2016

15. Beam-forming errors in Murchison widefield array phased array antennas and their effects on epoch of reionization science
Neben, Abraham R*; Hewitt, Jacqueline N*; Deshpande AA; Prabhu T; Udaya Shankar N; Srivani KS; Subrahmanyan, Ravi; +21 Co-authors
Astrophysical Journal **820**, 44, 2016

16. 3-cm fine structure masers: A unique signature of supermassive black hole formation via direct collapse in the early universe
Dijkstra, M*; Sethi, Shiv; Loeb, A*
Astrophysical Journal **820**, 10, 2016

17. Confirmation of wide-field signatures in redshifted 21 cm power spectra
Thyagarajan, Nithyanandan*; Jacobs, Daniel C*; Paul, Sourabh; Deshpande AA; Sethi SK; Srivani KS; Subrahmanyan, Ravi; Prabhu T; Udaya Shankar N; + 30 Co-authors
Astrophysical Journal Letters **807**, L-28, 2015

18. Murchison Wide Field array observations of anomalous variability: a serendipitous night-time detection of interplanetary scintillation
Kaplan DL*; Tingay SJ*; Deshpande AA; Prabhu T; Udaya Shankar N; Srivani KS; Subrahmanyan, Ravi; +20 Co-authors
Astrophysical Journal Letters **809**, L12, 2015

19. The abundance of x-shaped radio sources: implications for the gravitational wave background
Roberts, David H*; Saripalli, Lakshmi; Subrahmanyan, Ravi
Astrophysical Journal Letters **810**, L6, 2015

20. Diffuse x-ray emission from star-forming galaxies
Sarkar, Kartick C; Nath, Biman B; Sharma, Prateek*; Shchekinov, Yuri*
Astrophysical Journal Letters **818**, L24, 2016

21. The gas mass of star-forming galaxies at z 1.3
Kanekar, Nissim*; Sethi, Shiv; Dwarakanath KS
Astrophysical Journal Letters **818**, L28, 2016

22. The abundance of x-shaped radio sources i. VLA survey of 52 sources with off-axis distortions
Roberts, David H*; Cohen, Jake P*; Lu, Jing*; Saripalli, Lakshmi; Subrahmanyan, Ravi
Astrophysical Journal Supplement Series **220**, 7, 2015

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Raichur H; Das M*; Alonso Herrero A*; Shastri P*; Kantharia NG*
Astrophysics and Space Science **357**, 32, 2015

24. Angular momentum distribution during the collapse of primordial star-forming clouds
Dutta, Jayanta
Astrophysics and Space Science **361**, 35, 2016

25. Real-time imaging of density ducts between the plasmasphere and ionosphere
Loi, Shyeh Tjing*; Murphy, Tara*; Cairns, Iver H*; Deshpande AA; Prabhu T; Udaya Shankar N; Srivani KS; Subrahmanyan, Ravi
Geophysical Research Letters **42**, 3707-3714, 2015

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Mahesh, Nivedita; Subrahmanyan, Ravi; Udaya Shankar N; Raghunathan A
IEEE Transactions on Antennas and Propagation **63**, 4835, 2015

27. A systematic study of coding performance in a MIMO-STBC-OFDM link
Chandrasekaran, Parvathi; Balasubramanyam, Ramesh
IETE Journal of Research **61**, 56, 2015

28. Reionization constraints on primordial magnetic fields
Pandey KL*; Choudhury TR*; Sethi, Shiv; Ferrara A*
Monthly Notices of the Royal Astronomical Society **451**, 1692, 2015

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Singh, Priyanka; Nath, Biman B; Majumdar, Subhabrata*; Silk, Joseph*
Monthly Notices of the Royal Astronomical Society **448**, 2384-2396, 2015

30. Giant radio galaxies - II. Tracers of large-scale structure
Malarecki JM*; Jones DH*; Saripalli, Lakshmi; Staveley-Smith, L*; Subrahmanyan, Ravi
Monthly Notices of the Royal Astronomical Society **449**, 955-986, 2015

31. The role of three-body H2 formation in the fragmentation of primordial gas
Dutta, Jayanta; Nath, Biman B; Clark, Paul C*; Klessen, Ralf S*
Monthly Notices of the Royal Astronomical Society **450**, 202, 2015

32. An analysis of the halo and relic radio emission from Abell 3376 from Murchison Widefield Array observations
George LT; Dwarakanath KS; Deshpande AA; Prabhu T; Udaya Shankar N; Srivani KS; Subrahmanyan, Ravi; +30 Co-authors
Monthly Notices of the Royal Astronomical Society **451**, 4207-4214, 2015

33. Quantifying ionospheric effects on time-domain astrophysics with the Murchison Widefield Array
Loi, Shye Tjing*; Murphy, Tara*; Deshpande AA; Prabhu T; Udaya Shankar N; Srivani KS; Subrahmanyan, Ravi
Monthly Notices of the Royal Astronomical Society **453**, 2731-2746, 2015

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Sarkar, Kartick Chandra; Nath, Biman B; Sharma, Prateek*
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35. Is 4U 0114+65 an eclipsing HMXB?
Pradhan, Pragati*; Paul, Biswajit; Paul BC*; Bozzo, Enrico*; Belloni, Tomaso M*
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37. Pulse-phase dependence of emission lines in the X-ray pulsar 4U 1626-67
Beri, Aru*; Paul, Biswajit; Dewangan, Gulab C*
Monthly Notices of the Royal Astronomical Society **451**, 508, 2015

38. KAT-7 observations of a mass-selected sample of galaxy clusters
Bernardi, G*; Venturi T*; Cassano R*; Dallacasa D*; Brunetti G*; Cuciti V*; Johnston-Hollitt M*; Oozeer N*; Parekh V; Smirnov OM*
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39. Narrow escape: how ionizing photons escape from disc galaxies
Roy, A; Nath, Biman B; Sharma P
Monthly Notices of the Royal Astronomical Society **451**, 1939, 2015

40. The disruption of multiplanet systems through resonance with a binary orbit
Touma, Jihad R*; Sridhar S
Nature **524**, 439, 2015

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Beri, Aru*; Paul, Biswajit; Orlandini, Mauro*; Maitra, Chandreyee*
New Astronomy **45**, 48-53, 2016

42. Empirical covariance modeling for 21 cm power spectrum estimation: A method demonstration and new limits from early Murchison Widefield Array 128-tile data
Dillon, Joshua S*; Neben, Abraham R*; Hewitt, Jacqueline N*; Udaya Shankar N; Subrahmanyan, Ravi; Deshpande AA; Prabhu T; Srivani KS
Physical Review D **91**, 123011, 2015

43. Ionospheric modelling using GPS to calibrate the MWA. I: Comparison of first order ionospheric effects between GPS models and MWA observations
Arora BS*; Morgan J*; Deshpande AA; Dwarakanath KS; Prabhu T; Udaya Shankar N; Srivani KS; Subrahmanyan, Ravi; +25 Co-authors
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Wayth RB*; Lenc E*; Bell ME*; Deshpande AA; Prabhu T; Udaya Shankar N; Srivani KS; Subrahmanyan, Ravi; Dwarakanath KS; +30 Co-authors
Publications of the Astronomical Society of Australia **32**, e025, 2015

45. Power spectrum analysis of ionospheric fluctuations with the Murchison Widefield Array
Loi, Shyeh Tjing*; Trott, Cathryn M*; Murphy, Tara*; Cairns, Iver H*; Bell, Martin*; Subrahmanyan, Ravi; Williams CL*, Deshpande AA; Prabu T; Udaya Shankar N; Srivani KS
Radio Science **50**, 574, 2015

46. Measuring phased-array antenna beam patterns with high dynamic range for the Murchison Widefield Array using 137 MHz ORBCOMM satellites
Neben, AR*; Bradley RF*; Hewitt JN*; Bernardi G*; Bowman JD*; Subrahmanyan, Ravi; Deshpande AA; Prabu T; Udaya Shankar N; Srivani KS
Radio Science **50**, 614, 2015

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Srinivasa HT; Palakshamurthy BS*; Velmurugan D*; Devarajegowda HC*; Hariprasad S*
Acta Chimica Slovenica **62**, 768-774, 2015

48. Crystal structure of bis-(4-meth-oxy-phenyl) malonate
Devarajegowd HC*; Suchetan PA*; Sreenivasa S*; Srinivasa HT; Palakshamurthy BS*
Acta Crystallogr E Crystallogr Communications **E71**, 0330, 2015

49. Crystal structure of 4-meth-oxy-phenyl 2-oxo-2H-chromene-3-carboxyl-ate
Devarajegowda HC*; Suchetan PA*; Sreenivasa S*; Srinivasa HT; Palakshamurthy BS*
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Devarajegowda HC*; Suchetan PA*; Srinivasa HT; Sreenivasa S*; Palakshamurthy BS*
Acta Crystallographica section E Crystallographic Communications **E71**, 0326, 2015

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Awasthi, Saurabh*; Gayathri SK*; Ramya R*; Duraichelvan R; Dhason A; Saraswathi NT*
Applied Biochemistry Biotechnology **177**, 1013-1024, 2015

52. Evaluation of the exfoliation and stability of Na-montmorillonite in aqueous dispersions
Ali, Samim; Bandyopadhyay, Ranjini
Applied Clay Science **114**, 85-92, 2015

53. Tuning phase retardation behaviour of nematic liquid crystal using quantum dot
Gupta, Swadesh kumar*; Singh, Dharmendra Pratap*; Manohar, Rajiv*; Kumar, Sandeep
Current Applied Physics **16**, 79-82, 2016

54. Characteristics of the secondary relaxation process in soft colloidal suspensions
Saha, Debasish ; Joshi, Yogesh M* ; Bandyopadhyay, Ranjini
Europhysics Letters **112**, 46004, 2015

55. Ultra-low casting of Pt based nano-ink for electrooxidation of glycerol and ethylene glycol fuels in alkaline medium
Siddhardha, Sai RS*; Teja, Brahma MS*; Tejkiran PJ*; Lakshminarayanan V; + 4 Co-authors
Fuel **158**, 659-663, 2015

56. Kinetics of the glass transition of fragile soft colloidal suspensions
Saha, Debasish; Joshi, Yogesh M*; Bandyopadhyay, Ranjini
Journal of Chemical Physics **143**, 214901, 2015

57. Ultra-selective dopamine detection in an excess of ascorbic acid and uric acid using pristine palladium nanoparticles decorated graphendified glassy carbon electrode
Kumar, Manne Anupam*; Siddhardha, RS Sai*; Nived KC*; Lakshminarayanan V; Ramamurthy, Sai Satish*
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59. Aggregates of single-walled carbon nanotube bundles in a surfactant solution
Vijayaraghavan D
Journal of Molecular Liquids **209**, 440-446, 2015

60. Naphthalene derivatives induce Acyl chain interdigitation in dipalmitoylphosphatidylcholine bilayers
Kamal, Md. Arif; Raghunathan VA
Journal of Physical Chemistry B **120**, 164-172, 2016

61. Spot-free catalysis using gold carbon nanotube & gold graphene composites for hydrogenevolution reaction
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Thermochimica Acta **631**, 59-70, 2016

In Conference Proceedings

1. Experiments with an atom, ion, and molecule hybrid trap within a Fabry-Perot cavity
Jyothi S; Ray, Tridib; Dutta, Sourav; Rangwala SA
22nd International Conference on Laser Spectroscopy, Singapore, June 28 – July 3, 2015

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* denotes co-authors who do not belong to RRI
+ denotes co-authors who are Visiting Professors

APPENDIX II

CONFERENCES ATTENDED AND INSTITUTIONS VISITED

Name	Conferences attended / Institutions visited	Title of paper / Talk
Abir Sarkar	International Conference on Gravitation and Cosmology-2015 Indian Institute of Science Education and Research, Mohali 14 – 18 December 2015	Studying the effects of late forming dark matter in our universe
	School and Workshop on Large Scale Structure: From galaxies to the cosmic web Inter-University Centre for Astronomy and Astrophysics, Pune 1 – 12 February 2016	
	Neighbourhood Astronomy Meeting International Center for Theoretical Sciences, Bengaluru 28 March 2016	Studying the effects of late forming dark matter in our universe
Andal Narayanan	Durham University United Kingdom 12 May 2015	Weak value amplification in resonance fluorescence
Anil Kumar	Conference on Frontiers in Light-Matter Interaction 2016 Indian Institute of Technology Ropar 4 – 5 March 2016	
Avinash Deshpande	Tata Institute of Fundamental Research, Mumbai 29 April – 2 May 2015	Interstellar medium
	National Workshop on Cosmology with the HI 21cm line Raman Research Institute Bengaluru 23 – 26 June 2015	Extracting large-scale distribution of cold HI in the milky-way (*Invited*)
	Indian Institute of Science Education and Research, Mohali 11 – 13 August 2015	1. Fascinating life-stories of pulsars 2. Radio astronomy & SWAN
	Indian Institute of Technology Ropar 14 – 15 August 2015	1. Fascinating life-stories of pulsars 2. Radio Astronomy & SWAN
	Physical Research Laboratory Ahmedabad 19 – 22 August 2015	Fascinating life-stories of pulsars

	National Centre for Radio Astronomy Pune 5 – 8 January 2016	Pulsar single pulse emission (2 talks)
	Maulana Azad National Urdu University, Hyderabad 22 March 2016	SWAN: A strategic initiative
	University of Hyderabad, Hyderabad 22 March 2016	SWAN: A strategic initiative
Biman Nath	Tata Institute of Fundamental Research, Mumbai 21 April 2015	Fermi Bubbles: the biggest shock in the sky
	G C College Assam 24 December 2015	Einstein's dream: gravity as geometry (*Invited*)
	Centenary of Physics Department Calcutta University, Kolkata 6 January 2016	Helium discovery: the Indian connection (*Invited*)
	School and Workshop on Large Scale Structure: From galaxies to the cosmic web Inter-University Centre for Astronomy and Astrophysics, Pune 1 – 12 February 2016	Galactic outflows (*Invited*)
Biswajit Paul	Conference on Recent Trends in the Study or Compact Objects: Theory and Observation Aryabhatta Research Institute of Observational Sciences, Nainital 6 - 8 May 2015	X-ray Polarimetry
	3rd Beyond ASTROSAT Meeting Indian Institute of Astrophysics Bengaluru 28 July 2015	X-ray astronomy instrumentations at RRI
	Neighbourhood Astronomy Meeting Indian Institute of Science, Bengaluru 10 October 2015	X-ray reprocessing and prospects with ASTROSAT
	Workshop on Advances in Astroparticle Physics and Cosmology Saha Institute of Nuclear Physics Kolkata 12 - 17 October 2015	1. ASTROSAT and Beyond: Science and Technology Prospects 2. Many facets of neutron stars: ASTROSAT and beyond
	AEI-ICTS Gravitational Waves Workshop International Centre for Theoretical Sciences, Bengaluru 4 November 2015	The LAXPC instrument onboard ASTROSAT

	ASTROSAT-CZTI Mini Workshop Inter-University Center for Astronomy and Astrophysics Pune 5 - 10 November 2015	X-ray pulsars with CZTI: Science and techniques
	School on General Relativity and its Applications North Bengal University, Darjelling 23 - 28 November 2015	1. X-ray astronomy 2. General relativity
	International Conference on Gravitation and Cosmology Indian Institute of Science Education and Research, Mohali 14 - 18 December 2015	General relativity in X-ray Astronomy: ASTROSAT and future experiments
	Workshop on Timing and Spectroscopy: Wideband X-ray Astronomy TIFR Balloon Facility, Hyderabad 12 - 14 January 2016	Broadband studies with LAXPC
	School on Neutron Stars National Centre for Radio Astrophysics Pune 6 - 13 January 2016	1. X-ray astronomical techniques 2. Accreting neutron stars
	Neutron Stars: A Pathfinder Workshop National Centre for Radio Astrophysics Pune 14 - 15 January 2016	X-ray studies of neutron stars with ASTROSAT and POLIX
	Workshop on Jet Trigerring Mechanisms in Black Hole Sources Tata Institute of Fundamental Research, Mumbai 22 January 2016	Blazars: Prospects for X-ray polarimetry
	Bangalore Neighbourhood Astronomy Meeting International Centre for Theoretical Sciences, Bengaluru 28 March 2016	Results from some early observations with ASTROSAT – LAXPC
	Visitors Program 2016 Delhi University, Delhi 30 March 2016	Science prospects with Astrosat and future experiments
Buti Suryabrahmam	Annual Meeting of the Indian Biophysical Society Indian Institute of Science Bengaluru 8 – 10 February 2016	

	Conference on Optics Within Life Sciences 2016 Tata Institute of Fundamental Research, Mumbai 16 – 19 March 2016	
Deepshika Malkar	Winter School 2015 on Frontiers of Material Science Jawaharlal Nehru Centre for Advanced Scientific Research Bengaluru 7 December 2015	Smectic mesomorphism in bent core hockey stick shaped molecules
	22nd National Conference on Liquid Crystal DIT University, Dehradun 21 December 2015	Smectic mesomorphism in bent core hockey stick shaped molecules
Dibyendu Roy	Conference on Indian Statistical Physics Community Meeting 2016 International Centre for Theoretical Sciences, Bengaluru 14 February 2016	Separating many-body localized phase from Anderson localized phase (*Invited*)
Dwarakanath KS	Radio Astronomy School Radio Astronomy Centre, Ooty 11 – 14 June 2015	Spectral line observations
	Radio Astronomy School National Centre for Radio Astronomy Pune 1 – 4 September 2015	Self calibration
	Raman Research Institute Bengaluru 5 February 2016	The gas mass of star-forming galaxies at $z \approx 1.3$
Gautam V Soni	Ramalingaswamy Fellowship Conclave Regional Centre for Biotechnology Delhi 18 – 20 December 2015	
	60th Biophysical Society Meeting USA 25 February – 5 March 2016	Fabrication of low noise borosilicate glass nanopores for single molecule sensing
	Conference on Optics Within Life Sciences 2016 Tata Institute of Fundamental Research, Mumbai 16 – 19 March 2016	Nanoscale biophysics on nanopore platform

Gayathri Raman	European Week of Astronomy and Space Science 2016 University of la Laguna, Spain 22 – 26 June 2015	SALT observation of X-ray pulse reprocessing in 4U 1626-67
	University of Southampton United Kingdom 1 – 3 July 2015	Timing studies of X-ray optical variability in LMXBs
	LAXPC Workshop on Timing and Spectroscopy: Wide band X-ray Astronomy TIFR Balloon Facility Hyderabad 12 – 14 January 2016	LAXPC observations of Cyg X-3
Girish BS	MWA Technical Meeting University of Melbourne Australia 9 – 10 June 2015	1. Possible upgrades to the existing MWA digital-receiver system 2. State of the art digital-receiver for MWA Phase 3
	National Workshop on Cosmology with the HI 21cm line Raman Research Institute Bengaluru 23 – 26 June 2015	Correlation receivers for detecting cosmological signals
	Workshop on Engineering Contribution to the Advancement of Modern Science Christ University, Bengaluru 30 January 2016	Wide band digital - receivers for radio astronomical applications
	Quality Improvement Programme - Recent Developments in the Areas of Research in Electronics Christ University, Bengaluru 30 March 2016	Trends in digital-receiver design for radio astronomical applications
Jacob Rajan	Data Center IT Summit Bangalore 2015 Data Center Dynamics, Bengaluru 16 July 2015	
	Workshop on Cloud Computing: OpenStack Implementation for setting up Private Cloud Center for Development of Advanced Computing, Bengaluru 27 – 28 August 2015	
	Information Security Training for Government Officers Center for Development of Advanced Computing, Bengaluru 28 – 29 January 2016	

Janakee Raste	National Workshop on Cosmology with the HI 21 cm line Raman Research Institute Bengaluru 23 – 26 June 2015	A model for 21-cm signal for early Reionization Epoch
Joseph Samuel	Workshop on Mathematical Structure and Foundations of Quantum Physics Universidad de Los Andes Bogota 22 – 30 June 2015	Classical and quantum cloning (*Invited*)
	Aditi School Bengaluru 20 July 2015	The accelerating universe
	Chennai Mathematical Institute Chennai 25 - 28 August 2015	Classical and quantum cloning
	Workshop on Light Atom Interactions University of Mysore, Mysuru 7 - 12 December 2015	Reflections on rotations
	Workshop on the Quantum Measure and Causal Set Theory Raman Research Institute Bengaluru 4 - 8 January 2016	
	Conference on Quantum Physics: Foundations and Applications Centre for High Energy Physics Bengaluru 31 January - 13 February 2016	Entropy and geometry of quantum states (*Invited*)
Karamveer Kaur	Neighbourhood Astronomy Meeting Indian Institute of Science Bengaluru 10 October 2015	
Kartick Chandra Sarkar	National Workshop on Cosmology with the HI 21cm line Raman Research Institute Bengaluru 23 – 26 June 2015	
	Cloudy Workshop Inter-University Centre for Astronomy and Astrophysics, Pune 21 – 26 September 2015	Effect of dust on the Kennicutt's relation
	Neighbourhood Astronomy Meeting Indian Institute of Science Bengaluru 10 October 2015	

	School and Workshop on Large Scale Structure: From galaxies to the cosmic web Inter-University Centre for Astronomy and Astrophysics, Pune 1 – 12 February 2016	Effect if hot halo gas on galactic outflows and related multi-wavelength emission
	Neighbourhood Astronomy Meeting International Center for Theoretical Sciences, Bengaluru 28 March 2016	
Krishnamurthy S	Dspace Workshop Design and Development of Digital Libraries using Dspace – Advance National Institute of Science Communication and Information Resources, Delhi 8 – 12 February 2016	
Kumar Raviranjan	Camp on Hand-on Experiment in Radioastronomy Radio Astronomy Centre, Ooty 1 – 14 June 2015	
	Radio Astronomy School National Centre for Radio Astronomy Pune 31 August - 11 September 2015	
Lakshmi Saripalli	Conference on High Energy Phenomena and Fundamental Physics XXIX General Assembly (GA) of the IAU, Honolulu 3 – 15 August 2015	Jet drifts and flips in radio galaxies: probes of historical evolution of spin axis in supermassive black holes
	Conference on X-ray Surveys of the Hot and Energetic Cosmos XXIX General Assembly (GA) of the IAU, Honolulu 3 – 15 August, 2015	Giant radio galaxies as effective probes of X-ray gas in large-scale structure
	Saranath International Nyingma Institute, Sarnath 15 – 18 October 2015	In awe and wonderment: an astronomer's dairy
	Conference on The Many Facets of Extragalactic Radio Surveys: Towards New Scientific Challenges CNR Research Area, Italy 20 – 23 October 2015	Giant probes of large scale structure

Madhavan Varadarajan	Jawaharlal Nehru University New Delhi 13 May 2015	A new classical identity for canonical gravity
	LOOPS'15 Institute for Quantum Gravity Germany 6 – 10 July 2015	Remarks on the continuum limit in Canonical LQG
	Einstein Conference: A Century of General Relativity Harnack House of the Max Planck Society, Berlin 30 November – 5 December 2015	
Manjunath M	International Conference on Information Unbounded: Past, Present and Future of Information Sciences University of Mysore, Mysuru 18 – 20 June 2015	
	National KOHA Conclave Informatics India Pvt. Ltd. Bengaluru 17 – 18 February 2016	
	Workshop on Copyright Limitations and Exceptions of Libraries and Archives National Law School of India University, Bengaluru 4 – 5 March 2016	
Manjunath Kaddipujar	Conference on Scientometrics and the Internet of Things NCSI Net Foundation, Bengaluru 25 - 26 September 2015	Comparative study of metrics calculators
	Dspace Workshop Design and Development of Digital Libraries using Dspace – Advance National Institute of Science Communication And Information Resources, Delhi 8 – 12 February 2016	
Mayuri S Rao	CMB Spectral Distortions Workshop University of Chicago, USA 17 – 19 May 2015	
	National Workshop on Cosmology with the HI 21cm line Raman Research Institute Bengaluru 23 – 26 June 2015	On the detection of spectral ripples from the recombination epoch

	National Radio Astronomy Observatory, New Mexico 14 June – 31 July 2015	On the detection of spectral ripples from the recombination epoch
	Neighbourhood Astronomy Meeting Indian Institute of Science Bengaluru 10 October 2015	On the detection of spectral ripples from the recombination epoch
Meera BM	Conference on Scientometrics and the Internet of Things NCSI Net Foundation and Institute of Scientometrics Bengaluru 25 - 26 September 2015	1. A comparative study of ontology of Institutional repository of RRI and IISc: a bibliometric study of soft condensed matter physics 2. Comparative study of Metrics calculators 3. Internet of Things – How relevant it is to Libraries?
	Nodal Officers Meeting Institute of Advanced Study in Science and Technology Guwahati 8 - 9 October 2015	Promoting usage of e-resources with special reference to NKRC at DST Institutes (*Invited*)
	Discussion with OCLC-Informatics Meeting Informatics India P. Ltd. Bengaluru 2 November 2015	
	International Workshop on Big and Open Data: Evolving Data Science Standards & Citation Attribution Practices Indian National Science Academy New Delhi 5 – 6 November 2015	
	National Library Week Celebrations World Trade Centre, Bengaluru 19 November 2015	
	Seminar on Altmetrics ITC Gardenia, Bengaluru 4 December 2016	
	National Conference on Recent Trends in Open Access 2016 University College of Arts Tumakuru 9 January 2016	Best practices in scholarly communications: an open access phenomenon (*Invited*)
	Technical Discussion Meeting on How Disruptive are Futuristic and Digital Library Spaces? Tata Consultancy Services, Bengaluru 10 January 2016	

	National KOHA Conclave Informatics India Pvt. Ltd., Bengaluru 17 – 18 February 2016	
	Seminar on Data Analytics and Business Intelligence MYRA School of Business Bengaluru 11 March 2016	
	Conference on Library Automation using OSS – Koha NCSI NET Foundation and Sharada Ranganathan, Bengaluru Endowment for Library Science 18 March 2016	
Meera Thomas	Discussion Meeting on New Colloids Raman Research Institute Bengaluru 19 – 21 July 2015	Polyelectrolyte induced swelling in a lamellar phase
	Complex Fluids Symposium -2016 Indian Institute of Science Education and Research, Pune 2 – 4 January 2016	Polyelectrolyte induced swelling in a lamellar phase
Nafisa Aftab	Neighbourhood Astronomy Meeting Indian Institute of Science Bengaluru 10 October 2015	
	Neutron Star Workshop 2016 National Centre for Radio Astronomy Pune 6 – 15 January 2016	Variability study of the high mass X-ray binary IGR J 19027-2016 with swift-XRT
	Neighbourhood Astronomy Meeting International Center for Theoretical Sciences, Bengaluru 28 March 2016	X-ray processing: Eclipse spectrum of high mass and low mass X-ray binaries
Nagaraj M N	Workshop on Questionnaire Design and Statistical Analysis Shri Dharmashtala Manjunatheshwara Institute for Management Development Mysore 18 – 19 May 2015	
	Workshop on How to Publish Your Paper in Journals? Shri Dharmashtala Manjunatheshwara Institute for Management Development Mysore 27 June 2015	

	123rd Birth Anniversary of Dr.S R Ranganathan and Librarian's Day Celebration Programme BMS College of Engineering 12 August 2015	
	Turnitin Plagiarism Check Seminar Christ University, Bengaluru 20 November 2015	
	National Convention Gulbarga University, Gulbarga 24 – 26 November 2015	Digital preserving of multimedia and photographic collections of Raman Research Institute Library: a case study
Paramesh Gadige	Indian Institute of Technology Kanpur 28 – 31 March 2016	
Pramod Pullarkat	Indo-French Workshop on Frontiers in Cytoskeleton Research: Coordination, adaptation, fine-tuning Indian Institute of Science Education and Research, Pune 29 – 31 October 2015	The role of microtubules in induced axonal beading and retraction (*Invited*)
	Biomembranes Discussion Meeting Indian Institute of Science, Bengaluru 19 -20 December 2015	Membrane dynamics of axons studied using optical tweezers
	BSSE Annual Symposium 2016 – Cell, Tissue and Systems Engineering IISc Center for Biosystems Science and Engineering Meeting Indian Institute of Science, Bengaluru 8 - 9 January 2016	Properties of cell membrane probed using optical tweezers (*Invited*)
	Complex Fluids Symposium -2016 Indian Institute of Science Education and Research, Pune 2 – 4 January 2016	Axonal shape instabilities and dynamics (*Invited*)
	Meeting of the Indian Biophysical Society Indian Institute of Science, Bengaluru 8 – 10 February 2016	The role of microtubules in induced axonal beading and retraction (*Invited*)
	National University of Singapore Singapore 13 – 17 February 2016	
	Conference on Optics Within Life Sciences 2016 Tata Institute of Fundamental Research, Mumbai 16 – 19 March 2016	Mechanics of axonal cytoskeleton & membrane (probed using optics based force-tools) (*Invited*)

	Conference on Cell Mechanics Raman Research Institute, Bengaluru 24 – 26 April 2015	
Pramod Tadapatri	22nd National Conference on Liquid Crystal DIT University, Dehradun 21 - 23 December 2015	Unusual phase sequence in bent-core liquid crystals exhibiting lamellar and columnar phases
Pratibha R	European Conference on Liquid Crystals University of Manchester, UK 7 – 11 September 2015	Dielectric modes dictated by layer deformation and chiral segregation in induced dark mesophases (*Invited*)
	Toyota Riken International Workshop on Bent-core Liquid Crystals Tokyo Institute of Technology, Japan 16 – 17 November 2015	Induced mark mesophases in bent-core liquid crystals (*Invited*)
Priyanka Singh	National Workshop on Cosmology with the HI 21cm line Raman Research Institute Bengaluru 23 – 26 June 2015	
	Neighbourhood Astronomy Meeting Indian Institute of Science, Bengaluru 10 October 2015	A cross-correlation study of circum-galactic baryons
	Tata Institute of Fundamental Research, Mumbai 16 – 27 December 2015	
	School and Workshop on Large Scale Structure: From galaxies to the cosmic web Inter-University Centre for Astronomy and Astrophysics, Pune 1 – 12 February 2016	A cross-correlation study of circumgalactic medium
Rachuri Venkata Jagadeesh	Conference on Frontiers in Chemical Sciences and Technology 2016 National Institute of Technology Warangal 28 – 29 January 2016	
	International Conference on Nanoscience and Technology 2016 Indian Institute of Science Education and Research, Pune 29 February – 2 March 2016	

Raghavendra Rao KB	Conference on Cognitive Neuroscience and Brain Computer Applications MS Ramaiah Institute of Technology Bengaluru 14 – 21 January 2016	
Raghunathan A	National Workshop on Cosmology with the HI 21cm line Raman Research Institute Bengaluru 23 – 26 June 2015	Feeds for detection of cosmological signals
	The International Conference on Electromagnetics in Advanced Application and the IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications Torino Incontra Congress Center Italy 7 – 11 September 2015	Design of frequency independent profiled discone antenna for detecting spectral ripples from the epoch of recombination
	2nd URSI Regional Conference on Radio Science Jawaharlal Nehru University New Delhi 16 – 19 November 2015	Challenges in the design of feed antenna for detecting cosmological signals
Raghunathan VA	Indira Gandhi Centre for Atomic Research, Kalpakkam 23 December 2015	Electrostatic self-assembly of oppositely charged macroions
	Complex Fluids Symposium -2016 Indian Institute of Science Education and Research, Pune 2 – 4 January 2016	
	Conference on Emergent Phenomena in Soft and Active Matter Jawaharlal Nehru Centre for Advanced Scientific Research Bengaluru 5 – 6 January 2016	Domain formation in binary lipid-sterol membranes (*Invited*)
	St. Joseph's College Bengaluru 29 January 2015 12, 19, 26 February 2016 4, 11 March 2016	Thermodynamics

Rahul Sawant	Cold-Atoms PreDoc School Exploring New Quantum Gases Centre de Physique des Houches France 14 – 25 September 2015	
	The Europeanc Organisation for Nuclear Physics, Geneva 25 September 2015	Interactions between different types of particles in hybrid traps
	Institute for Quantum Electronics Switzerland 26 September 2015	
	University of Basel, Switzerland 28 September 2015	
	Universität Heidelberg, Germany 29 September 2015	
	Institut für Quantenmaterie Germany 30 September 2015	
	Johannes Gutenberg Universität Germany 1 – 2 October 2015	
	Universitè Paris-Sud, France 5 October 2015	
	Universitè Paris, France 6 October 2015	
Ramesh B	Max Planck Institute for Radio Astronomy, Germany 12 – 14 May 2015	One element interferometer
	1st URSI Atlantic Radio Science Conference ExpoMeloneras Convention Centre Spain 18 – 22 May 2015	Surface metrology with one element interferometry
	Lecture Program on Geometry and Optics Raman Research Institute, Bengaluru 18 – 20 January 2016	
	Christ University, Bengaluru 30 January 2016	Telescopes, the artificial eyes
Ranjini Bandyopadhyay	The International Centre for Theoretical Physics, Bengaluru 2 April 2015	A colloidal clay suspension as a model glass former: some recent experiments

	The Hungarian Academy of Sciences Budapest 27 April – 2 May 2015	The dynamic slowing down process in soft colloidal glasses: some comparisons with supercooled liquids
	Conference on Dynamics of Viscous Liquids 2015 University of Montpellier, France 4 – 6 May 2015	The dynamic slowing down in viscous suspensions
	International Year of Physics Mallya Aditi School, Bengaluru 8 July 2015	What is soft matter?
	19th Meeting of the Committee on Freedom and Responsibility in the Conduct of Science International Council of Science Paris 1 – 2 October 2015	
	Workshop on Growing Length Scale Phenomena in Condensed Matter Physics Jawaharlal Nehru Centre for Advanced Scientific Research Bengaluru 8 – 10 October 2015	Microstructures and yielding of gel networks of charged anisotropic colloidal particles in aqueous suspensions
	SN Bose Centre for Basic Sciences Kolkata 4 November 2015	Microscopic structures and yielding of colloidal clay dispersions in the presence of salt
	Workshop on Statistical Physics of Soft Matter Benaras Hindu University 27 November 2015	Soft matter: their flow and deformation
	Complex Fluids Symposium Indian Institute of Science Education and Research, Pune 2 – 4 January 2016	The effect of yielding in the microstructure and yielding of aqueous dispersions of colloidal clay
	Conference on Emergent Phenomena in Soft Matter Jawaharlal Nehru Centre for Advanced Scientific Research, Bengaluru 5 – 6 January 2016	Microstructure and yielding of colloidal clay suspensions
	Nanoparticle Assembly – From Fundamentals to Applications in Faraday Discussions Indian Institute of Technology, Powai 7 – 9 January 2016	Aggregation and stability of anisotropic clay colloids in aqueous medium in the presence of salt
Ravi Subrahmanyan	Jawaharlal Nehru Planetarium Bengaluru 10 May 2015	Radio waves from the early universe

	CMB Distortions Workshop University of Chicago, USA 17 – 19 May 2015	APSERA: Array of precision spectrometers for the epoch of recombination (*Invited*)
	National Workshop on Cosmology with the HI 21cm line Raman Research Institute Bengaluru 23 – 26 June 2015	Efforts to detect Cosmological 21-cm
	Conference on High Energy Phenomena and Fundamental Physics XXIX General Assembly (GA) of the IAU, Honolulu 3 – 15 August 2015	Detecting CMB distortions from Cosmic Baryon Evolution
	NCRA-TIFR School on Radio Astronomy National Centre for Radio Astrophysics, Pune 31 August – 03 September 2015	1. Interferometers I 2. High dynamic range imaging
	International Conference on Gravitation and Cosmology Indian Institute of Science Education and Research, Mohali 14 – 18 December 2015	Spectral signatures of cosmic Baryon evolution (Invited)
	Christ University Bengaluru 30 January 2016	Engineering for visions of the cosmos
Reji Philip	Workshop on Current Trends in Applied Physics Cochin University of Science and Technology, Cochin 30 April 2015	Laser produced plasmas (*Invited*)
	13th International Conference on Laser Ablation 2015 Pullman Hotel, Australia 31 August – 04 September 2015	Influence of laser pulse width on the ablation of Zinc in nitrogen ambient
	Griffith University Australia 7 - 14 September 2015	Nanosecond and femtosecond laser produced plasmas from metallic targets
	Australian National University Australia 16 September 2015	Nonlinear optics of mesoscopic systems
	Light Matters 2015 Workshop SSSIHL Prasanti Nilayam 26 - 27 October 2015	Nanosecond and femtosecond laser produced plasmas from metallic targets (*Invited*)
	National Conference on Advanced Nanomaterials Nirmalagiri College, Kuttuparamba 1 - 2 October 2015	Nonlinear optics in the nanophase (*Invited*)

	National Seminar on Photonics and its Applications 2015 University of Kerala, Thiruvananthapuram 9 - 11 December 2015	Nanophotonics(*Invited*)
	Seminar on Recent Trends in Biophotonics Govt. College, Madappally 17 - 18 December 2015	Fundamentals of nonlinear optics (*Invited*)
	International Conference on Nanoscience and Nanotechnology Cochin University of Science and Technology, Cochin 20 - 23 February 2016	Nonlinear Optics of Nanomaterials (*Invited*)
	National Conference on Smart Materials Lady Doak College, Madurai 23 - 24 February 2016	Nanophotonics (*Invited*)
	Frontiers in Materials Science St. Joseph's College, Calicut 24 - 25 February 2016	Nanophotonics (*Invited*)
Sadiq Rangwala	Saha Institute of Nuclear Physics Kolkata 26 August 2015	Physics in and with ion-atom hybrid traps
	Laboratoire Amie Cotton, France 2 November 2015	Creation and destruction of molecular ions in hybrid ion-atom traps
	Laboratoire de Physique des Lasers Univercite Paris XIII France 3 November, 2015	
	Laboratoire Kastler-Brossel Ecole Normal Superior Collage de France, France 4 November 2015	
	Conference on Cold Atoms: Fundamental Concepts and Applications Ecole Normal Superior, France 5 – 6 November 2015	Interactions between ions and atoms in hybrid traps
	9th India-NUS Physics Symposium National University of Singapore 24 – 26 February 2016	Experiments on interacting ion-atom systems in hybrid traps
	SPS March Meeting 2016 Quantum Optics and Optics of Quantum Systems Jawaharlal Nehru University New Delhi 18 – 19 March 2016	Collisional cooling of trapped ions with atoms

Sandeep Kumar	New Horizon College of Engineering Bengaluru 11 July 2015	
	Indian Institute of Technology Kharagpur 24 July 2015	Dispersion of zero-, one- and two-dimensional nanoparticles in the supramolecular order of discotic liquid crystals (*Invited*)
	Workshop on Modern Trends in Chemical Research Christ University, Bengaluru 15 September 2015	The fascinating world of liquid crystals **(***Invited*)
	University of Allahabad Allahabad 16 July 2015 21 September 2015	
	Working Group Meeting on Electronic Materials & Components Department of Electronics and Information Technology New Delhi 28 September 2015	
	Vikram University, Ujjain 12 December 2015	
	Government Holkar Science College Indore 14 December 2015	Nanoparticles in discotic liquid crystals: A new class of organic semiconductors (*Invited*)
	Complex Fluids Symposium -2016 Indian Institute of Science Education and Research, Pune 2 – 4 January 2016	Discotic liquid crystalline nanocomposites as advanced materials for opto-electronics (*Invited*)
	Workshop on Synthesis, Characterization and Application of Nanoparticle Assemblies National Chemical Laboratory Pune 4 January 2016	Application of nanoparticles; Liquid crystalline nanocomposites as advanced materials for opto-electronics (*Invited*)
	National Conference on Recent Trends in Chemical Sciences 2016 Manipal Institute of Technology Manipal 11 January 2016	Supramolecular nanocomposites as advanced materials for opto-electronics **(**Keynote address)
	INSPIRE Internship Science Camp Raj Kumar Goel Engineering College Pilkhuwa 21 January 2016	Introduction to liquid crystals (*Invited*)

	Refresher Course for University Teachers University of Mysore, Mysuru 24 February 2016	1. Liquid crystals: the beautiful fourth state of matter (Invited) 2. Discotic liquid crystals (*Invited*)
	Indian Institute of Technology Madras 2 March 2016	Discotic liquid crystalline nanocomposites as advanced materials for opto-electronics (*Invited*)
	2nd Annual World Congress of Smart Materials-2016 Grand Copthorne Waterfront Hotel Singapore 4 – 6 March 2016	Discotic nanocomposites as a new class organic semiconductors(*Invited*)
	University of Malaysia, Malaysia 9 March 2016	Discotic liquid crystalline nanocomposites as advanced materials for opto-electronics (*Invited*)
	PRSG Meeting of Deity Solar Cell Projects University of Tejpur, Assam 17 March 2016	
Sanjay Kumar Behera	Conference on Growing Length Scale Phenomena in Condensed Matter Physics Jawaharlal Nehru Centre for Advanced Scientific Research, Bengaluru 7 – 10 October 2015	
	Complex Fluids Symposium -2016 Indian Institute of Science Education and Research, Pune 2 – 4 January 2016	
Sanjib Sabhapandit	IGERT Summer Institute Brandeis 27 July – 7 August 2015	Fluctuations and large deviations in nonequilibrium systems (*Invited*)
	Indian Institute of Technology Guwahati 31 August 2015	Fluctuation and large deviations in non-equilibrium systems
	Saha Institute of Nuclear Physics Kolkata 1 – 2 September 2015	Fluctuation and large deviations in non-equilibrium systems
	ICTS Workshop on Non-equilibrium Statistical Physics 26 October – 20 November 2015	Universal large deviations for the tagged particle in single file motion (*Invited*)
	Bangalore Probability Seminar Indian Institute of Science Bengaluru 1 February 2016	Extreme value statistics (near extreme events and records) (*Invited*)

	Indian Statistical Physics Community Meeting International Center for Theoretical Sciences, Bengaluru 12 – 14 February 2016	Dynamical transition in the temporal relaxation of stochastic processes under resetting
	Institute of Physics Bhubaneswar 1 – 2 March 2016	Fluctuations & large deviations in non-equilibrium systems
	Université Paris-Sud France 15 – 31 March 2016	Fluctuation theorem for entropy production of a partial system in the weak coupling limit
Saptarishi Chaudhuri	Lecture Workshop JSS College of Arts, Commerce and Science, Mysore 25 – 26 November 2015	Bose Einstein statistics
Simanraj Sadana	International Meeting on Quantum Information Processing and Applications Harish-Chandra Institute Allahabad 7 – 13 December 2015	Diffraction based linear optics quantum information
Somashekar R	Jawaharlal Nehru Planetarium Bengaluru 27 June 2015	
	Workshop on Engineering Contribution to the Advancement of Modern Science Christ University, Bengaluru 30 January 2016	Challenges in building received systems for radio astronomy
Sourabh Paul	National Workshop on Cosmology with the HI 21cm line Raman Research Institute Bengaluru 23 – 26 June 2015	21 cm Epoch of Reionization and foregrounds study with the Murchison Widefield Array
	University of Washington, USA 4 – 18 October 2015	
	Arizona State University, USA 19 – 24 October 2015	

Sourav Dutta	Conference on Frontiers in Atomic, Molecular and Optical Sciences Indian Association for the Cultivation of Science, Kolkata 19 - 20 February 2016	Collisional cooling of low-mass ions and photodissociation of molecular ions in a hybrid ion-atom trap (*Invited*)
Sreeja Sasidharan	Conference on Optics Within Life Sciences 2016 Tata Institute of Fundamental Research Mumbai 16 – 19 March 2016	
Sridhar S	American University of Beirut Lebanon 24 April – 20 May 2015	Introduction to galaxies I, II (2 talks)
	Neighbourhood Astronomy Meeting Indian Institute of Science Bengaluru 10 October 2015	The disruption of multiplanet systems through resonance with a binary orbit (*Invited*)
	Indian Institute of Science Bengaluru 30 October 2015	Stars, planets and black holes: dynamics and statistical mechanics of N-body gravitating systems
Srivani K S	National Workshop on Cosmology with the HI 21cm line Raman Research Institute Bengaluru 23 – 26 June 2015	
	Workshop on Engineering Contribution to the Advancement of Modern Science Christ University, Bengaluru 30 January 2016	Digital system design using FPGAs
	Quality Improvement Programme - Recent Developments in the Areas of Research in Electronics Christ University, Bengaluru 30 March 2016	Recent advances in digital electronics
Sumati Surya	Perimeter Institute Canada 15 October 2015	The Hawking-Hartle no boundary proposal in causal set quantum gravity
	Conference on Leadership and Career Development for Women Scientists & Technologists Indian Institute of Science Education and Research, Pune 28 August - 1 September 2015	

Sumati Surya	ICMS Workshop Prospects for Causal Set Quantum Gravity International Centre for Mathematical Sciences, UK 7 - 11 September 2015	Topology in causal set theory: a review
	Discussion Meeting on Quantum Measure and Causal Set Theory Raman Research Institute Bengaluru 4 – 8 January 2016	
Supurna Sinha	Workshop on Mathematical Structure and Foundations of Quantum Physics Universidad de Los Andes, Bogota 22 – 30 June 2015	Coarse quantum measurement (*Invited*)
	Aditi School Bengaluru 22 July 2015	A sound and light show
	MLA College Bengaluru 30 September 2015	Special theory of relativity
	Workshop on Light Atom Interaction University of Mysore, Mysore 7 – 12 December 2015	Special theory of relativity: Lorentz transformation from the Doppler shift
	Workshop on Quantum Physics: Foundations and Applications Centre for High Energy Physics Bengaluru 31 January – 13 February 2016	Reflections off moving mirrors: A discrete gauge effect on the boundary of a manifold (*Invited*)
Surya Narayan Sahoo	Meeting on Quantum Information Processing and Applications Harish-Chandra Institute Allahabad 7 – 13 December 2015	Generation of spatially correlated qutrits
Sushil Dubey	Conference on Cell Mechanics Raman Research Institute Bengaluru 24 – 26 April 2015	Active and passive responses of axonal cytoskeleton
	Conference on Mechanical Manipulation National Centre for Biological Sciences Bengaluru 26 April – 7 May 2015	

	Indo-French Conference on Cell and Cytoskeleton Indian Institute of Science Education and Research, Pune 25 – 27 October 2015	Mechanical responses of neurons
	BSSE Symposium Indian Institute of Science Bengaluru 8 – 9 January 2016	Mechanical responses of neurons
	Conference on Optics Within Life Sciences 2016 Tata Institute of Fundamental Research, Mumbai 16 – 19 March 2016	Active and passive responses of axonal cytoskeleton
Urbasi Sinha	Workshop on Multi Photon Interferometry University of Science and Technology China 7 – 10 May 2015	Three-slit experiments (*Invited*)
	CQIQC Quantum Optics Seminar University of Toranto 20 May 2015	Surprises regarding the superposition principle in interference experiments (*Invited*)
	Institute for Quantum Computing University of Waterloo 21 May 2015	Surprises regarding the superposition principle in interference experiments (*Invited*)
	International Conference on Quantum Foundations 2015 National Institute of Technology Patna 30 November – 4 December 2015	Surprises regarding the superposition principle in interference experiments (*Invited*)
	International Meeting on Quantum Information Processing and Applications 2015 Harish-Chandra Institute Allahabad 7 – 13 December 2015	Surprises regarding the superposition principle in interference experiments (*Invited*)
Vani Hiremath	123rd Birth Anniversary of Dr. S R Ranganathan and Librarian's Day Celebration Programme BMS College of Engineering 12 August 2015	
	Conference on Scientometrics and the Internet of Things NCSI Net Foundation, Bengaluru 25 - 26 September 2015	

Varun	Neighbourhood Astronomy Meeting Indian Institute of Science Bengaluru 10 October 2015	
	Workshop on Timing and Spectroscopy: Wide band X-ray Astronomy TIFR Balloon Facility Hyderabad 12 – 14 January 2016	LAXPC background variability and its sensibility to faint sources
	Neighbourhood Astronomy Meeting International Center for Theoretical Sciences, Bengaluru 28 March 2016	
Vijayaraghavan D	World Congress on Microscopy: Instrumentation, Techniques and Applications in Life Sciences and Material Sciences Mahatma Gandhi University Kottayam 11 October 2015	Aggregate of single-walled carbon nanotube bundles in a surfactant solution (*Invited*)
Yashodhan Hatwalne	Complex Fluids Symposium -2016 Indian Institute of Science Education and Research, Pune 3 January 2016	Lamellar soft matter with in-plane orientational order: equilibrium of fluid interfaces, and elasticity of liquid crystals (*Invited*)
	Indian Statistical Physics Community Meeting International Center for Theoretical Sciences, Bengaluru 12 February 2016	Continuum "xy-model" on deformable surfaces: equilibrium of fluid interfaces, and elasticity of liquid crystals (*Invited*)

APPENDIX III

COLLOQUIA AND SEMINARS

Name	Title	Date
Francois Bouchet Institut de'Astrophysique de Paris, France	Cosmology with the Planck satellite	7 April 2015
Arijit Sharma National University of Singapore, Singapore	Towards a phase gate with Barium ions	10 April 2015
Debashree Chowdhury Indian Statistical Institute, Kolkata	Spin transport in semiconductors and electron vortex beams	20 April 2015
E Krishnakumar Tata Institute of Fundamental Research Mumbai	Negative ion resonances in molecular hydrogen	27 April 2015
Dipanjan Bhattacharya National University of Singapore Singapore	Mechanobiolological understanding of neurulation during zebrafish embryogenesis	30 April 2015
Chira R Bhattacharjee Assam University, Silchar	Schiff base and their coordination compounds' as versatile synthons for accessing liquid crystalline material	7 May 2015
Bhupendra Yadav Azim Premji University, Bengaluru	A history of history	7 May 2015
Mithun Biswas Goethe-Universität, Frankfurt	Selective regulation of stability of nucleic acid complexes: An atomistic view	11 May 2015
Abhishek Kumar Beijing Computational Science Research Centre, China	Non-Markovian decoherence in optically probed systems	26 May 2015
Pratap Raychaudhuri Tata Institute of Fundamental Research Mumbai	Disordered superconductors: A TIFR story	27 May 2015
Hamsa Padmanabhan Inter-University Centre for Astronomy & Astrophysics, Pune	Neutral hydrogen in the post-reionization universe	4 June 2015
Nupur Biswas Indian Institute of Science Bengaluru	Soft materials in nanoscale	9 June 2015
Ravi P Rau Louisiana State University, USA	The beauty of physics: Patterns, principles and perspectives	11 June 2015
Chirag Kalelkar Indian Institute of Technology, Kharagpur	Summer course of fluid instabilities	15 June – 1 July 2015
Koyel Das Vehere Interactive Pvt. Ltd., Kolkata	Digital polarization conversion, bandpass calibration methods and coherence detection in Bremsstrahlung	16 June 2015
Sudha Rajamani Indian Institute of Science Education and Research, Pune	Origin and replication of informational molecules on prebiotic earth	18 June 2015

Thushara Pillai Max-Planck Institute for Radio Astronomy Germany	Unraveling the structure of molecular clouds in the milky way and beyond	19 June 2015
Sudipto Muhuri Savitribai Phule Pune University, Pune	Jamming transition in a driven lattice gas	19 June 2015
Dipanjan Mitra National Centre for Radio Astrophysics, Pune	Unraveling the nature of coherent radio emission in pulsars	16 July 2015
Tripta Bhatia University of Southern Denmark Denmark	Organization, mechanics and dynamics of membranes with ion pumps	22 July 2015
Chitra Rangan University of Windsor, Canada	Surface enhanced quantum control	22 July 2015
Utkarsh Mishra Harish-Chandra Research Institute, Allahabad	Benford's law detects quantum phase transitions similarly as earthquakes	23 July 2015
Brajesh Gupt Pennsylvania State University, USA	Loop quantum cosmology: Very early universe and recent observations	27 July 2015
MS Jayalakshmi Cochin University of Science and Technology, Cochin	Electro-active polymer-ceramic nano composites for pyroelectric thermal/infrared detection and nonlinear optical applications	28 July 2015
PH Prasad Medical Officer, Raman Research Institute, Bengaluru	Concept of health	30 July 2015
T Prabu Raman Research Institute Bengaluru	FPGA based high performance computing	4 August 2015
Sanjukta Roy University of Florence, Italy	Measurement of the mobility edge for 3D Anderson localization	4 August 2015
Ramakrishna Podila Clemson University, USA	Defects and interface-induced phenomena in low-dimensional materials	5 August 2015
Biman Nath Raman Research Institute Bengaluru	Blowing in the wind	6 August 2015
Jihad R Touma American University of Beirut, Lebanon	Dynamics and thermodynamics of self-gravitating Keplerian discs	14 August 2015
Bibhu Ranjan Sarangi Instit Jacques Monod, Paris	Mechanosensing at different length scales: From multi-cellular aggregates to sub-cellular focal adhesions	17 August 2015
Deepto Chakrabarty Massachusetts Institute of Technology, USA	On the origin of Quiscent emission in neutron star X-ray transients	17 August 2015
Sovan Chakrabarty Max Planck Institute for Physics Germany	Neutrino Astrophysics: What we have learned and the way forward	20 August 2015
Jayanth Neelakanta Syracuse University, USA	Diffeomorphism-invariance constraints on cosmological correlators	24 August 2015

Sanjib Sabhapandit Raman Research Institute Bengaluru	Fluctuations and large deviations in non-equilibrium systems	27 August 2015
DP Sen Gupta National Institute of Advanced Studies Bengaluru	The history of time, time-keeping and standard time	3 September 2015
Anbumozhi Angayarkanni Indira Gandhi Centre for Atomic Research, Kalpakkam	Factors influencing the thermal properties of nanofluids and phase change materials	3 September 2015
Tuhin Ghosh Institut d'Astrophysique Spatiale, France	BICEP2 and post Planck status of CMB B-mode polarization	4 September 2015
KK Anoop University of Naples Federico II, Italy	Femtosecond laser ablation of solid targets using Gaussian and Vortex beams	24 September 2015
G Paramesh Gadige Service de Physique de l'Etat Condense France	Linear and nonlinear dielectric response in glass-forming liquids	28 September 2015
Shankar Ghosh Tata Institute of Fundamental Research Mumbai	Granular self-organization by autotuning of friction	6 October 2015
Steve Granick IBS Center for Soft and Living Matter South Korea	Some surprises and open questions in soft matter	7 October 2015
Abhay Ashtekar Pennsylvania State University, USA	Loop quantum cosmology and the very early universe interplay between theory and observations	9 October 2015
Aravindan M Warrier Macquarie University, Australia	Developing ultrafast Raman lasers	13 October 2015
Vishal Gajjar Xinjiang Astronomical Observatory China	On the absence of pulses from pulsars	28 October 2015
Ashok Singal Physical Research Laboratory Ahmedabad	Radiation reaction and the pitch angle changes in synchrotron source	29 October 2015
Rama Jois Former Chief Justice, Punjab and Haryana	Trivarga ensures good governance	31 October 2015
Saroj Kumar Nandi Max-Planck-Institut für Physik Complex Systeme, Germany	Quantum mechanics-like behaviour of a classical object: A droplet walking on a vertically vibrated liquid surface	4 November 2015
Rohini M Godbole Indian Institute of Science Bengaluru	Chameleon neutrinos - Physics Nobel Prize 2015	5 November 2015
Kamaraju Natarajan Los Alamos National Laboratory, USA	Controlling and using THz pulses to probe novel materials	11 November 2015
Nimisha G Kantharia National Centre for Radio Astrophysics Pune	Some insights into recurrent novae from modelling radio synchrotron light curves	13 November 2015

Suresh Bhat National Chemical Laboratory, Pune	Understanding structure & rheology of concentrated colloidal suspensions: Milk to yoghurt to microgel suspensions	18 November 2015
Debarati Chatterjee Max Planck Institute for Polymer Research, Germany	A theoretical approach to understand various bio-inspired soft condensed matter systems	18 November 2015
Arijit Kundu Technion, Israel	Topology and transport in periodically driven systems	18 November 2015
Md. Injamamul Arief SN Bose National Centre for Basic Sciences, Kolkata	Magnetorheological fluids with ferromagnetic binary alloys and oxides	20 November 2015
Nimesh A Patel Harvard-Smithsonian Center for Astrophysics, USA	The submillimeter array and the Greenland telescope	23 November 2015
Nishant K Singh Nordic Institute for Theoretical Physics Sweden	A new precursor to solar active region formation	24 November 2015
Michael Doser European Organization for Nuclear Research, Switzerland	AEGIS: A new experiment to measure the gravitational interaction of antihydrogen	26 November 2015
Aditya Rotti Florida State University, USA	Measuring isotropy violations in the CMB sky	27 November 2015
Vijayakumar Chikkadi Laboratoire de Physique, Ecole Normale Superieure de Lyon, France	Insights into flow of glasses and active matter using colloids	4 December 2015
Borun D Chowdhury Arizona State University, USA	The information paradox: It just won't go away	7 December 2015
Etienne Brion Laboratoire Aimé Cotton, France	Quantum optical non-linearities induced by Rydberg-Rydberg interactions: A perturbative approach	17 December 2015
K Rajibul Islam MIT- Harvard Center for Ultracold Atoms, USA	Assembling a quantum many-body system atom-by-atom	4 January 2016
Fabien Bretenaker Laboratoire Aimé Cotton, France	Low-noise lasers and amplifiers for microwave photonics applications	14 December 2015
Vaibhav Madhok University of British Columbia Canada	Quantum correlations, chaos and information	16 December 2015
Sougato Bose University College London, UK	Three schemes for probing the macroscopic limits of quantum mechanics	29 December 2015
Crystal Senko MIT- Harvard Center for Ultracold Atoms, USA	Realization of a quantum integer-spin chain with controllable interactions	4 January 2016
Sandeep Goyal University of Calgary, Canada	Quantum information processing: Implementation schemes and quantum memory	5 January 2016

Arun K Nandi Indian Association for the Cultivation of Science, Kolkata	Graphene oxide and graphene quantum dot-conducting polymer hybrids for photovoltaic applications	6 January 2016
DN Rao Indian Institute of Science Bengaluru	DNA repair mechanism Nobel Prize in Chemistry – 2015	7 January 2016
Srihari Srinivasan Institute of Applied Physics Germany	Theoretical models for ultracold atom-ion collisions in confined geometries	8 January 2016
Navinder Singh Physical Research Laboratory Ahmedabad	Generalized drude scattering rate of electrons in metals: the memory function formalism	14 January 2016
C Trager-Cowan University of Strathclyde, UK	Nanocharacterisation of the structural and luminescence properties of materials in the scanning electron microscope	14 January 2016
Jean-Francois Tassin Universitè du Maine, France	Selective localization of fillers in polymer blends	19 January 2016
Sonali Sachdeva Inter-University Centre for Astronomy & Astrophysics, Pune	Evolution of disc galaxies for the past 8 Gyrs	21 January 2016
Amendra Kumar Pandey Physical Research Laboratory Ahmedabad	Study of electronic structure of molecular systems involving dissociation/reaction in various excitation processes	28 January 2016
Sourabh Lahiri Laboratoire de Physico-Chimie Thèorique, Paris	Fluctuation relations for entropy and work in small systems	2 February 2016
Dipanjan Bhattacharya NUS Singapore-MIT Alliance for Research and Technology Center Singapore	Mechanobiological understanding of tissue patterning during Zebrafish neurulation	2 February 2016
Shubhashis Rana Institute of Physics, Bhubaneswar	Stochastic thermodynamics of small scale heat engines and refrigerators	3 February 2016
Eli Barkai Bar-Ilan University, Israel	Fractional diffusion of cold atoms in optical lattices	4 February 2016
Girish Kulkarni Institute of Astronomy, UK	Small-scale structure of the IGM and its measurement using quasar pairs	18 February 2016
Giorgio Immirzi (formerly) University of Perugia & INFN, Italy	Spin foam and energetic causal sets	18 February 2016
AR Yuvaraj University of Malaysia Pahang, Malaysia	Synthesis and characterization of azobenzene derivatives for photo-induced effects	22 February 2016
Parameswaran Ajith International Centre for Theoretical Sciences, Bengaluru	LIGO observation of gravitational waves from a binary black hole merger	25 February 2016
Fabienne Goldfarb Laboratoire Aimé Cotton, France	Coherent processes and light storage in metastable helium atoms at room temperature	26 February 2016

Nirmal Iyer Inter-University Centre for Astronomy & Astrophysics, Pune	Monitoring and studying X-ray binary transients	31 March 2016

CELL MECHANICS MEETING

24 – 26 April, 2015

Name	Title
24 APRIL 2015	
Roop Mallik Tata Institute of Fundamental Research, Mumbai	Cholesterol assembles armies of motor proteins on phagosomes
Gautam Soni Raman Research Institute Bengaluru	Nanopore Biophysics: From molecular detection to biology
E Ravikrishnan Indian Institute of Technology, New Delhi	Minimum and maximum limit to number of Myosin II Motors participating in an ensemble motility
Aurnab Ghose Indian Institute of Science Education & Research Pune	On growth and FORMIN(g) neuronal filopodia
Ranjith Padinhatheeri Indian Institute of Technology Bombay	Microtubule shrinkage: Powerful elastic bending or stochastic thermal unzippering?
Anita Joanna Kosmalska The Institute for Bioengineering of Catalonia, Barcelona	Physical principles of membrane remodeling during cell mechano-adaptation
Rishita Changede Mechanobiology Institute, Singapore	Integrin clusters of 100nm form early adhesions and depend on Talin
Rumi Dey Indian Institute of Science Education & Research Kolkata	Dynamics of focal adhesions under time varying stretch
Sampada Mutalik Indian Institute of Science Education & Research Pune	Regulation and functions of mechanical forces in neurons
Mandar Inamdar Indian Institute of Technology Bombay	Cell-cell adhesion, ECM topography and propensity of ECM proteolysis dictate the migration pattern of cancer cell collectives
Mithilesh Mishra Tata Institute of Fundamental Research, Mumbai	Studying cytokinesis in vitro
Thomas Pucadyil Indian Institute of Science Education & Research, Pune	Membrane curvature controls epsin - induced clathrin assembly
Mohammed Saleem National Institute of Technology Rourkela	Membrane elasticity and polymerization energy modulate the shape
Sukrut Kamerkar Indian Institute of Science Education & Research Pune	Biochemical screen for potential membrane fission catalysts

Rahul Roy Indian Institute of Science Bengaluru	Hybrid fluorescence - force measurements for DNA - protein interactions
ASR Koti Tata Institute of Fundamental Research, Mumbai	Quantification of protein dynamics in terms of flexibility/rigidity by single molecule force Spectroscopy experiments
Debasish Chaudhuri Indian Institute of Technology Hyderabad	Forced desorption of semiflexible polymers, adsorbed and driven by molecular motors
Manindra Bera Saha Institute of Nuclear Physics Kolkata	Force spectroscopy of lamins
Jyoti Sharma Indian Institute of Technology New Delhi	Role of fumarate ion in changing bacterial flagellar motor from clockwise rotation to counterclockwise rotation
GV Shivashankar Mechanobiology Institute Singapore	Nuclear mechanics and genome regulation
25 APRIL 2015	
Abhijit Majumdar Indian Institute of Technology Bombay	Feel thy neighbor: Intercellular force interaction via deformable matrix
Ramanujan Srinivasan National Institute of Science Education and Research Bhubaneshwar	Cytoskeleton in Prokaryotes: Assembly, dynamics & diversity
Sriram Ramaswamy Tata Institute of Fundamental Research, Hyderabad	Activating membranes
Madan Rao Raman Research Institute Bengaluru	Actomyosin pulsation and symmetry breaking flows drive tissue remodelling
Pere Roca-Cusachs University of Barcelona Spain	Understanding the cell extracellular matrix mechanical link: From molecular roles to emerging behaviors
Deepak Sinha Indian Association for the Cultivation of Science Kolkata	Three - dimensional environment induces monocyte to macrophage differentiation
Vijaykumar Krishnamurthy International Centre for Theoretical Sciences, Bengaluru	PAR polarity in C. Elegans zygotes
Maitrey Narasimha Tata Institute of Fundamental Research, Mumbai	Anisotropies in cytoskeletal organization induced by ROS and Rho signalling underlie multicellular sensing and spatial patterning in a Drosophila epithelium
Sitikantha Roy Indian Institute of Technology New Delhi	Atomic force microscopy in cell mechanics

Namrata Gundiah Indian Institute of Science Bengaluru	Directing cell migrations
Dipanjan Bhattacharya Mechanobiology Institute, Singapore	Mechanobiological understanding of neurulation during zebrafish embryogenesis
Bidisha Sinha Indian Institute of Science Education & Research, Kolkata	Mapping membrane fluctuations in adherent cells
Gautam Menon Institute of Mathematical Sciences Chennai	Spatiotemporal fluctuations in chromatin compaction states of stem cells
Abhishek Chaudhuri Indian Institute of Science Education & Research, Mohali	Active clustering and pattern regulation in living cells
Sarbari Bhattacharya University of Bangalore, Bengaluru	Fine tuning membrane stiffness of red blood cells with bovine serum albumin
Nagaraj Balasubramanian Indian Institute of Science Education & Research, Pune	Integrin dependent caveolar trafficking in 3D microenvironments
Madhulika Dixit Indian Institute of Technology Madras	Glucose metabolism and vascular progenitors: Is mechanosensing the missing link?
Shamik Sen Indian Institute of Technology Bombay	Crosstalk between matrix metalloproteases (MMPs) and the actomyosin cytoskeleton in breast cancer
Satyajit Mayor National Centre for Biological Sciences, Bengaluru	Transient modulation of clathrinindependent endocytosis during cellular strain-relaxation offers a mechanism for regulating membrane tension

NATIONAL WORKSHOP ON COSMOLOGY WITH THE HI 21-cm line

23 – 26 June 2015

Name	Title
23 June 2015	
N Udaya Shankar Raman Research Institute Bengaluru	Welcome address
Somnath Bharadwaj Indian Institute of Technology Kharagpur	Introduction to 21cm cosmology
Saurabh Singh Raman Research Institute Bengaluru	On the detection of global EoR with interferometers
Ravi Subrahmanyan Raman Research Institute Bengaluru	Ongoing efforts at RRI to detect the global HI signal
Raghunathan Agaram Raman Research Institute Bengaluru	Feed antennas for the detection of cosmological signals
BS Girish Raman Research Institute Bengaluru	Spectrometer for measuring cosmological signals
Jayaram Chengalur National Centre for Radio Astrophysics, Pune	Towards detecting HI in the post reionisation era
Viswesh Marthi National Centre for Radio Astrophysics, Pune	Simulations for the OWFA: instrument, foregrounds and the signal
Saiyad Ali Jadavpur University, Kolkata	Overview of foregrounds for the 21-cm signal
Anjan Kumar Sarkar Indian Institute of Technology Kharagpur	Fisher matrix predictions for detecting the cosmological 21 cm signal with the Ooty Wide Field Array (OWFA)
24 June 2015	
Mayuri S Rao (remote presentation) Raman Research Institute Bengaluru	On the detection of spectral ripples from the Recombination Epoch
Jasjeet Bagla Indian Institute of Science Education and Research, Mohali	The statistical HI signal
N Udaya Shankar Raman Research Institute Bengaluru	Global efforts to detect all sky signal from EoR
Nishikant Khandai National Institute of Science Education and Research Bhubaneswar	Simulations of HI intensity mapping

Tapomoy Guha Sarkar Birla Institute of Technology and Science, Pilani	Cosmology using the Cross correlation of 21-cm signal
T Roy Choudhury National Centre for Radio Astrophysics, Pune	Observational constraints on reionization
Abhik Ghosh Indian Institute of Technology Kharagpur	Foregrounds for 21cm signal: what we learn up to now
Kanan Datta Presidency University Kolkata	Simulating HI 21-cm signal during cosmic reionization
Debanjan Sarkar Indian Institute of Technology Kharagpur	Modeling the neutral hydrogen distribution in the post reionization Universe
Suman Majumdar Stockholm University Sweden	Detecting ionized bubbles in the redshifted 21-cm maps of EoR
25 June 2015	
Shiv K Sethi Raman Research Institute Bengaluru	Global efforts to detect the HI power spectrum: MWA, LOFAR, SKA
Suman Chatterjee Indian Institute of Technology Kharagpur	Prospects of detecting the post-reionization HI 21cm signal using upgraded GMRT
Janakee Raste Raman Research Institute Bengaluru	A model for 21cm signal from early reionization epoch in 2- and 3-point correlation function
Aseem Paranjape Inter-University Centre for Astronomy and Astrophysics Pune	Analytical models of reionization
Sourabh Paul Raman Research Institute Bengaluru	21 cm epoch of reionization signal and foregrounds study with Murchison Widefield Array
Raghunath Gara National Centre for Radio Astrophysics, Pune	21-cm signal from cosmic dawn : Imprints of the light-cone effects
Avinash Deshpande Raman Research Institute Bengaluru	Extracting large-scale distribution of cold HI in the milky-way
Kanhaiya Lal Pandey National Centre for Radio Astrophysics, Pune	Reionization and primordial magnetic fields
Prasun Dutta National Centre for Radio Astrophysics, Pune	Probing turbulence in ISM of galaxies with 21 cm line

Samir Choudhuri Indian Institute of Technology Kharagpur	Visibility based angular power spectrum estimator in 21-cm experiments
Rajesh Mondal Indian Institute of Technology Kharagpur	Statistics of the epoch of reionization (EoR) 21-cm signal: power spectrum error covariance
26 June 2015	
Nissim Kanekar National Centre for Radio Astrophysics, Pune	Neutral hydrogen in high-redshift galaxies
Neeraj Gupta Inter-University Centre for Astronomy and Astrophysics Pune	HI with SKA pathfinders: ASKAP and MEERKAT
Arunima Banerjee Inter-University Centre for Astronomy and Astrophysics Pune	Probing the dark matter density profiles of nearby edge-on galaxies with the HI 21 cm line
Mousumi Das Indian Institute of Astrophysics Bengaluru	The HI content and dark matter content of the nearby LSB galaxy NGC4701
Honey M Indian Institute of Astrophysics, Bengaluru	HI studies of low surface brightness galaxies with the Nancy Radio Telescope

BANGALORE SCHOOL ON STATISTICAL PHYSICS VI

2 – 18 JULY 2015

Name	Title	Date
Abhishek Dhar International Centre for Theoretical Sciences Bengaluru	Introductory lectures on statistical physics	2, 3 and 6 July 2015
Sanjib Sabhapandit Raman Research Institute Bengaluru	Introductory lectures on statistical physics	2, 3 and 7 July 2015
David Mukamel Weizmann Institute of Science, Israel	Statistical mechanics of systems with long-range interactions	6 – 11 July 2015
Shin-Ichi Sasa Kyoto University, Japan	Large deviation functions and fluctuation relations in non-equilibrium systems	6 – 11 July 2015
Deepak Dhar Tata Institute of Fundamental Research Mumbai	Directed percolation and sandpile models	8 – 11 July 2015
Mustansir Barma Tata Institute of Fundamental Research Mumbai	Interacting particle systems	13, 14, 16, 17 and 18 July 2015
Debashish Chowdhury Indian Institute of Technology, Kanpur	Physics of molecular motors	15, 16, 17 and 18 July 2015
David Pine New York University, USA	Introduction of soft matter physics	13, 14, 15, 16 and 18 July 2015

DISCUSSION MEETING ON 'NEW COLLOIDS'

19 – 21 JULY 2015

Name	Title
19 July 2015	
David Pine New York University, USA	DNA coated colloids with and without directional interactions
Ganesh Subramanian Jawaharlal Nehru Centre for Advanced Scientific Research, Bengaluru	The role of weak Brownian motion in dilute (anisotropic) suspension rheology - Connections to the coil-stretch hysteresis
Surajit Dhara University of Hyderabad Hyderabad	Topological defect mediated self-assembly and structural transition of liquid crystal colloids
Snigdha Thakur Indian Institute of Science Education and Research Bhopal	Biomimetic behavior of synthetic particles
Abhrajit Laskar Institute of Mathematical Sciences Chennai and Raj Kumar Manna Indian Institute of Technology, Madras	Flow-induced propulsion, aggregation, and self-assembly in chains made of active colloids
20 July 2015	
David Pine New York University, USA	Random organization: Reversibility in non-Brownian suspensions
Rajesh Ganapathy Jawaharlal Nehru Centre for Advanced Scientific Research Bengaluru	Insights into the structural glass transition from new colloids experiments
Guruswamy Kumaraswamy National Chemical Laboratory, Pune	Macro-assemblies from bonding colloids
Ambarish Ghosh Indian Institute of Science, Bengaluru	Magnetic nano-swimmers
Rema Krishnaswamy Indian Institute of Science Bengaluru	Yielding of a dense polydisperse 2D suspension under periodic shear
21 July 2015	
David Pine New York University USA	Colloidal surfers
Sriram Ramaswamy TIFR Centre for Interdisciplinary Sciences Hyderabad	Active colloids

Prerna Sharma Indian Institute of Science Bengaluru	Chirality induced assembly of crenellated colloidal membranes
Ayan Banerjee Indian Institute of Science Education and Research Kolkata	The magic of the transient: Microbubbles in optical tweezers
Soumyajit Roy Indian Institute of Science Education and Research Kolkata	Soft-oxometalates (SOMS): What are they? Where are we?

APPENDIX IV

RRI SCIENCE FORUM

Sl. No.	Discussed by	Paper discussed	Date
1	Avinash A Deshpande & Kumar Raviranjan	Detection of off-pulse radio emission from pulsars: A status report	09 April 2015
2	Arun Roy	Topology and dynamics of active nematic vesicles	14 May 2015
3	Ranjini Bandyopadhyay & Sanjay Kumar Behara	Glass-glass transition during aging of a colloidal clay	28 May 2015
4	Yashodhan Hatwalne	Hyperbolic Interfaces	25 June 2015
5	A Raghunathan	Unravelling the mystery of electromagnetism	23 July 2015
6	Urbasi Sinha & Surya Narayan Sahoo	Can past be erased? Is it a matter of choice?	13 August 2015
7	Joseph Samuel & Anirudh Reddy	A self interfering clock as a "which path" witness	10 September 2015
8	Pramod Pullarkat & Sushil Dubey	Diffusible crosslinkers generate directed forces in microtubule networks	24 September 2015
9	Andal Narayanan & J Ayyappan	Long-lived quasistationary coherences in a V-type system driven by incoherent light	8 October 2015
10	Sourav Dutta	Collisional cooling of light ions by co-trapped heavy atoms	12 November 2015
11	Supurna Sinha	Resolution of the Abraham–Minkowski controversy	26 November 2015
12	Anil Kumar	Controlling velocity of light in cavity–optomechanics	10 December 2015
13	Nupur Biswas	Nanopore translocation for single molecule detection	11 February 2016

APPENDIX V

VISITORS

Visitors' Name / Affiliation	Duration
Asha K Kuvempu University, Shimoga	31 March - 31 May 2015 2 - 7 July 2015 22 - 24 August 2015 5 - 27 October 2015
Asif Ahangar University of Kashmir, Srinagar	1 April – 31 May 2015
Francois Bouchet Institut de'Astrophysique de Paris, France	6 – 7 April 2015 23 – 24 June 2015
Arijit Sharma National University of Singapore, Singapore	10 April 2015
Abhishek Kumar Beijing Institute for Computation Research, China	14 April – 14 June 2015
Dipanjan Bhattacharya National University of Singapore Singapore-MIT Alliance for Research and Technology Center, Singapore	23 April – 1 May 2015
E. Krishnakumar Tata Institute of Fundamental Research, Mumbai	26 – 27 April 2015
Chira R Bhattacharjee Assam University, Silchar	30 April -10 May 2015
Wu Shuin Jian Yale-NUS College, Singapore	11 May – 31 July 2015
Sudhi Oberoi Harish-Chandra Research Institute, Allahabad	15 May – 15 June 2015
Uddipta Chatterjee Indian Institute of Technology, Bombay	19 – 20 May 2015
Pratap Raychaudhuri Tata Institute of Fundamental Research, Mumbai	27 – 28 May 2015
Govind Swarup National Centre for Radio Astrophysics, Pune	29 – 30 May 2015
Hamsa Padmanabhan Inter University Centre for Astronomy & Astrophysics, Pune	1 – 5 June 2015
Vikram Vyas St. Stephens College, Delhi University, Delhi	1 – 26 June 2015
L Sriramkumar Indian Institute of Technology Madras, Chennai	6 – 10 June 2015
Ravi P Rau Louisiana State University, USA	7 – 14 June 2015
Manash Kanti Biswas Shajalal University of Science & Technology Bangladesh	7 – 14 June 2015

Md. Enamul Hoque Shajalal University of Science & Technology Bangladesh	7 – 14 June 2015
Koyel Das Vehere Interactive Pvt. Ltd., Kolkata	8 – 12 June 2015
Nairit Das Indian Institute of Technology, Kharagpur	8 June – 9 July 2015 1 – 31 December 2015
Nupur Biswas Indian Institute of Science, Bangalore	9 June 2015
T. Nithyanandan Arizona State University, USA	12 - 13 June 2015 1 – 4 July 2015
Chirag Kalelkar Indian Institute of Technology, Kharagpur	14 June – 5 July 2015
Sudipto Muhuri Savitribai Phule Pune University, Pune	19 June 2015
Thushara Pillai Max-Planck Institute for Radio Astronomy Germany	19 June 2015
Jens Kaufmann Max-Planck Institute for Radio Astronomy Germany	19 June 2015
Sandeep Rana Indian Institute of Science Education and Research Mohali	19 – 28 June 2015
Jasjeet Bagla Indian Institute of Science Education and Research Mohali	21 – 29 June 2015
SudhaRajamani Indian Institute of Science Education and Research Pune	20 – 23 June 2015
Steve Granick IBS Center for Soft and Living Matter South Korea	6 – 10 July 2015
Chitra Rangan University of Windsor, Canada	6 July – 14 August 2015
Vanessa Manipal University, Manipal	10 – 20 July 2015
Dipanjan Mitra National Centre for Radio Astrophysics, Pune	15 – 17 July 2015
Tripta Bhatia University of Southern Denmark, Denmark	18 – 26 July 2015
Wasim Raja Cotton College State University, Guwahati	22 July – 5 August 2015
Sandeep Krishna National Centre for Biological Sciences, Bangalore	24 July 2015
Utkarsh Mishra Harish-Chandra Research Institute, Allahabad	22 – 25 July 2015

Jayalakshmi Cochin University of Science & Technology Cochin	28 – 29 July 2015
Ramakrishna Podila Clemson University, USA	3 – 6 August2015
Ravi A Kumar Institute for Plasma Research, Gandhinagar	6 – 7 August 2015
Jihad R Touma American University of Beirut, Lebanon	7 – 22 August 2015 7 – 23 January 2016
Roslit and Joana Bharthidasan University, Thiruchirapalli	13 – 14 August 2015
Govind Menon Brown University, USA	13 – 31 August 2015
Jayanth Neelakanta Syracuse University, USA	14 August 2015
Deepto Chakrabarty Massachusetts Institute of Technology, USA	17 – 18 August 2015
Sovan Chakrabarty Max Planck Institute for Physics, Munich	19 – 22 August 2015
Anbumozhi Angayarkanni Indira Gandhi Centre for Atomic Research Kalpakkam	2 – 5 September 2015
Tuhin Ghosh Institut d'Astrophysique Spatiale, France	3 -4 September 2015
KK Anoop University of Naples Federico II, Italy	23 – 24 September 2015
Dhiraj Dedhia Tata Institute of Fundamental Research Mumbai	23 – 29 September 2015
Pragati Pradhan North Bengal University, Siliguri St. Joseph's College, Darjeeling	25 September – 31 October 2015 1 January – 21 February 2016
Kavya H Rao University of Griffith, Australia	2 October – 13 November 2015
Smijesh Nadarajan Achary University of Griffith, Australia	2 October – 13 November 2015
Shankar Ghosh Tata Institute of Fundamental Research, Mumbai	6 October 2015
Ruta Kale National Centre for Radio Astrophysics, Pune	6 – 10 October 2015
Aravindan M Warrier Macquarie University, Australia	12 – 14 October 2015
Jayata Dutta Inter University Centre for Astronomy & Astrophysics, Pune	26 October – 15 December 2015
Ashok Singal Physical Research Laboratory, Ahmedabad	29 October 2016
Saroj Kumar Nandi Max-Planck-Institut für Physik Complex Systeme Germany	3 – 5 November 2015

Nimisha G Kantharia National Centre for Radio Astrophysics, Pune	13 – 14 November 2015
Manzoor Malik Kashmir University, Jammu & Kashmir	13 – 15 November 2015
Suresh Bhat National Chemical Laboratory, Pune	15 – 18 November 2015
Arijit Kundu Technion, Israel	17 – 20 November 2015
Nimesh Patel Harvard-Smithsonian Center for Astrophysics USA	22 – 25 November 2015
Nishant K Singh Nordic Institute for Theoretical Physics, Sweden	23 – 24 November 2015
Aditya Rotti Florida State University, USA	27 November 2015
Ginson P Joseph St. Thomas College, Kerala	02 - 03 December 2015 19 - 23 December 2015 03 - 05 March 2016
Fabien Bretenaker CNRS Laboratoire Aime Cotton, France	7 – 21 December 2015
Mr. Wei Lin Laboratoire Aime Cotton, France	11 - 18 December 2015
Marie Aude Laboratoire Aime Cotton, France	11 – 18 December 2015
Etienne Brion Laboratoire Aime Cotton, France	11 - 18 December 2015
Vaibhav Madhok University of British Columbia, Canada	13 – 16 December 2015
Sougato Bose University College London, UK	28 December 2015 – 1 January 2016
Dipankar Home Bose Institute, Kolkata	28 December 2015 - 01 January 2016 07 - 12 February 2016
Rafael Sorkin Perimeter Insitute for Theoretical Physics, Canada	1 January 2016 - 14 February 2016
Yu Asato University of California, USA	1 – 11 January 2016
Henry Wilkes Imperial College, UK	2 – 15 January 2016
Ian Jubb Imperial College, UK	2 – 15 January 2016
Rajibul Ismal MIT-Harvard Centre for Ultracold Atoms, USA	3 – 4 January 2016
Crystal Senko MIT-Harvard Centre for Ultracold Atoms, USA	3 – 4 January 2016
Sandeep Goyal University of Calgary, Canada	3 - 6 January 2016
Fay Dowker Imperial College, UK	3 – 9 January 2016

Lisa Glaser The University of Nottingham, UK	3 – 9 January 2016
David Rideout University of California, USA	3 – 14 January 2016
Nosiphiwo Zwane Perimeter Insitute for Theoretical Physics, Canada	3 – 17 January 2016
Yasaman Yazdi Perimeter Institute for Theoretical Physics, Canada	3 – 17 January 2016
Petros Wallden University of Edinburgh, UK	4 – 10 January 2016
Will Cunningham North Eastern University, USA	5 – 13 January 2016
Arun K Nandi Indian Association for the Cultivation of Science Kolkata	6 – 7 January 2016
David H Roberts Brandeis University, USA	11 – 30 January 2016
C Trager-Cowan University of Strathclyde, UK	14 January 2016
NP Dhanya K.K.T.M. Government College, Trichur	15 January – 15 February 2016
Nipanjana Patra Univeristy of Berkeley, USA	18 – 21 January 2016
Jean-Francois Tassin Université du Maine, Institut des Molécules et Matériaux du Mans, France	19 January 2016
Sonali Sachdeva Inter University Centre for Astronomy & Astrophysics, Pune	21 January 2016
Giorgio Immirzi (Formerly) University of Perugia & INFN Perugia, Italy	29 January – 23 February 2016
Sujay Mate Indian Institute of Science Education and Research Pune	1 February – 15 March 2016
Eli Barkai Bar-Ilan University, Israel	4 February 2016
Alexandre Matzkin University of Cergy-Pontoise, France	8 – 12 February 2016
Girish Kulkarni Institute of Astronomy, UK	17 – 19 February 2016
AR Yuvaraj University of Malaysia Pahang, Malaysia	22 February 2016
Fabienne Goldfarb Laboratoire Aime Cotton, France	24 – 29 February 2016

Jayaram N Chengalur National Centre for Radio Astrophysics, Pune	7 – 9 March 2016
TR Seshadri Delhi University, New Delhi	8 – 10 March 2016
Nirmal Iyer Inter University Centre for Astronomy & Astrophysics, Pune	30 – 31 March 2016

APPENDIX VI

VISITING STUDENTS' PROGRAMME

Sl. No.	Student	Mentor
1	Aathira Hegde	Deshpande A A
2	Abhishek Som	Deshpande A A
3	Abhishek Tripathi	Sandeep Kumar
4	Aditi Nethwewala	Arun Roy
5	Adwait P. Suratkar	Gautam Soni
6	Alka Bhat	Pramod Pullarkat
7	Aniruddha M	Srivani K S
8	Aniruddha Upadhye	Pramod Pullarkat
9	Anirudh A Pise	Hema Ramachandran
10	Anjali Sharma	Pratibha R
11	Anjan Kumar	Hema Ramachandran
12	Anjana Kudva	Deshpande A A
13	Anuragh Saha Roy	Urbasi Sinha
14	Anushka Jha	Ranjini Bandyopadhyay
15	Aparna Markose	Reji Philip
16	Arunita Kumari	Deshpande A A
17	Arvind Kumar	Gautam Soni
18	Ashwini G	Gautam Soni
19	Aswani I C	Hema Ramachandran
20	Aswathy Sasidharan	Raghunathan A
21	Atishay Dixit	Sandeep Kumar
22	Avinash	Shiv Sethi
23	Avinash Nargund	Srivani K S / Girish B S
24	Basave Gowda H S	Ramesh B
25	Bhagyashri Devaru Bhat	Arun Roy
26	Bharath Krishnan	Ramesh B
27	Brinda K Kariappa	Hema Ramachandran
28	Chandrashekar M	Ramesh B
29	Debapriya Pal	Hema Ramachandran
30	Dhanush B K	Girish B S
31	Divya Jayashankar	Raghunathan A
32	Elizabeth Joseph	Arun Roy

33	Eshita Paul	Gautam Soni
34	Gayatri Patel	Deshpande A A
35	Girish Hemraj	Ruckmongathan T N
36	Harikrishnan A	Andal N
37	Harini Desiraju	Joseph Samuel
38	Haritha M	Reji Philip
39	Isha Kotecha	Sumati Surya
40	Ishika Palit	Deshpande A A
41	Janet Joy	Ravi Subrahmanyan
42	Jayanth J	Andal N
43	Juhi Tiwari	Shiv Sethi
44	Karthik Thalambeti	Ravi Subrahmanyan
45	Kiran Narayana Hegde	Somashekar R
46	Krishnaprasad C	Lakshmi Saripalli
47	Krishnendu Ray	Sumati Surya
48	Kshama K Zingade	Dwarakanath K S
49	Kshitij Aggarwal	Ravi Subrahmanyan
50	Lakshay Khurana	Hema Ramachandran
51	Lijin Rose Baby	Pratibha R
52	Madhurima Choudhury	Deshpande A A
53	Madhuvanthi G Athani	Shiv Sethi
54	Manasa Manjunath	Sumati Surya
55	Mani Kumar T	Hema Ramachandran
56	Manikandan K	Gautam Soni & Hema Ramachandran
57	Manish Kumar	Sandeep Kumar
58	Manjunath A S	Vijayaraghavan D
59	Meenu Murali	Pratibha R
60	Megha Ghosh	Andal N
61	Mohammed Abdul Majeed	Ramesh B
62	Mohan Kumar S	Srivani K S
63	Moumita Adhikari	Gautam Soni
64	Naimahmed Nesaragi	Ramesh B
65	Nandini S G	Urbasi Sinha
66	Naveen Kumar Tripathi	Deshpande A A
67	Neema Prakash	Saptarishi Chaudhuri
68	Neha Ruchi	Gautam Soni

69	Pankaj Satapathy	Gautam Soni
70	Phalguni Mathur	Ramesh B
71	Poojitha C G	Vijayaraghavan D
72	Pradeep Singh	Srivani K S
73	Prashanth Kumar S	Raghunathan A
74	Prathwiraj U	Urbasi Sinha
75	Praveen M N	Ramesh B
76	Prem J	Ramesh B
77	Priyanka Bhatt	Sadiq Rangwala
78	Priyanka Mohandas	Deshpande A A
79	Pulkit Gupta	Raghunathan A
80	Pushpitha Das	Biman Nath
81	Rahul S. Kingar	Deshpande A A
82	Ramana Reddy R	Hema Ramachandran
83	Reshma Ravi	Hema Ramachandran
84	Ritesh Soni	Gautam Soni
85	Rohit K A	Ramesh B
86	Rohit Prasad Bhatt	Hema Ramachandran
87	Rose Martina P A	Hema Ramachandran
88	Sanal V	Hema Ramachandran
89	Saniya Heba	Urbasi Sinha
90	Santosh Harish	Udaya Shankar N
91	Seraj Uddin Ansari	Hema Ramachandran
92	Shalaka Varshney	Sandeep Kumar
93	Shankar M J	Hema Ramachandran
94	Sharanya A	Gautam Soni
95	Shivam Arora	Deshpande A A
96	Shivi Shetty	Sadiq Rangwala
97	Shreemala Dhayal	Sandeep Kumar
98	Shruthi L S	Rishin P V
99	Shubhagata Bhoumik	Andal N
100	Simran Singh	Sumati Surya
101	Sindhana Selvi P S	Supurna Sinha
102	Siva Pradyumna	Urbasi Sinha
103	Smruti Rekha M	Pratibha R
104	Soham Kumar Dutta	Arun Roy

105	Sourabha T T	Gautam Soni
106	Spoorthy P	Somashekar R
107	Sreedevi M N	Nayantara Gupta
108	Sreelakshmi Chandrabose	Reji Philip
109	Sudhi Oberoi	Urbasi Sinha
110	Sujay Mate	Biswajit Paul
111	Sujit Narayanan	Pramod Pullarkat
112	Sunil Kumar	Raghunathan A
113	Swapnil Narke	Ramesh B
114	Swati Kaushik	Gautam Soni
115	Swetha G S M	Hema Ramachandran
116	Tejkiran P J	Lakshminarayanan V
117	Vaishnavi B M	Girish B S
118	Venkatesh R	Ranjini Bandyopadhyay
119	Vishnu Puneeth Reddy	Srivani K S
120	Vittala	Hema Ramachandran
121	Vivek D	Srivani K S
122	Wrijupan Bhattacharyya	Nayantara Gupta

RAMAN RESEARCH INSTITUTE
Bangalore

Audit Statements of Accounts
2015-2016

G.R. VENKATANARAYANA
CHARTERED ACCOUNTANTS
Partners :
CA. G.R. Venkatanarayana, B.Com., F.C.A.,
CA. G.S. Umesh, B.Com., F.C.A.,
CA. Venugopal N. Hegde, B.Com., F.C.A.,

No. 618, 75th Cross, 6th Block,
Rajajinagar, Bengaluru-560 010.
Ph: 23404921 / 64537325
Fax: 23500525
Email: grvauditor@gmail.com
1grvenkat@gmail.com

AUDITOR'S REPORT

TO THE MEMBERS OF RAMAN RESEARCH INSTITUTE, BANGALORE

We have audited the financial statements of the "**RAMAN RESEARCH INSTITUTE",** Sir C V Raman Avenue, Sadashivanagar, Bangalore – 560080 which comprise of Balance sheet as at 31st March 2016, the Income & Expenditure Account for the year ended and the Receipts and Payment account for the year ended on that date annexed thereto. These financial statements are the responsibility of the management of Raman Research Institute. Our responsibility is to express an opinion on these financial statements based on our audit.

We conducted our audit in accordance with auditing, standards generally accepted in India. Those standards require that we plan and perform the audit to obtain reasonable assurance about whether the financial statements are free of material misstatement. An Audit includes examining, on a test basis, evidence supporting the amounts and disclosures in the financial statements. An audit also includes assessing the accounting principles used and significant estimates made by Management as well as evaluating the overall financial statements presentation. We believe that our audit provides reasonable basis for our opinion.

We report that:

1. We have obtained all the information and explanations, which to the best of our knowledge and belief were necessary for the purpose of our audit.

2. In our opinion proper books of accounts as required by law have been kept by the Raman Research Institute so for as it appears from our examination of those books.

3. The Balance Sheet, Income and Expenditure Account and Receipts and Payment account dealt with by this report are in agreement with the books of account.

4. The Balance Sheet and Income and Expenditure Account dealt with by this report are prepared in accordance with the Accounting Standards issued by the Institute of Chartered Accountants of India.

.....2

G.R. VENKATANARAYANA Chartered Accountants BANGALORE

5. In our opinion and to the best of our information and according to the explanations given to us the said accounts give a true and fair view in conformity with the accounting principles generally accepted in India:

   a) In the case of Balance Sheet, of the state of affairs of the Raman Research Institute as at March 31, 2016; and

   b) In the case of Income and Expenditure Account, of the excess of Expenditure over Income for the year ended on that date.

For M/s G R Venkatanarayana
Chartered Accountants
Firm Regn. No. 004616S

(G R Venkatanarayana)
Partner
Membership No. 018067

M/s. G.R. VENKATANARAYANA
Chartered Accountants
618, 75th Cross, 6th Block,
Rajajinagar, BANGALORE-560 010

Place: Bangalore
Date: 22.07.2016

RAMAN RESEARCH INSTITUTE, BANGALORE
BALANCE SHEET AS AT 31ST MARCH 2016

(Amount in INR)

CORPUS/CAPITAL FUND AND LIABILITIES	Schedule	Current Year	Previous Year
Corpus/Capital Fund	1	101,64,55,150	102,56,48,572
Reserves & Surplus	2	-	-
Earmarked & Endowment Funds	3	49,10,15,247	48,90,27,083
Secured Loans & Borrowings	4	-	-
Unsecured Loans & Borrowings	5	-	-
Deferred Credit Liabilities	6	-	-
Current Liabilities & Provisions	7	1,65,78,598	3,38,04,209
TOTAL		**152,40,48,995**	**154,84,79,864**
ASSETS			
Fixed Assets	8	91,92,72,404	93,53,60,866
Investments- from earmarked & endowment funds	9	46,36,38,678	46,71,03,670
Investments-Others	10	1,00,46,575	-
Current Assets, Loans & Advances	11	13,10,91,338	14,60,15,328
TOTAL		**152,40,48,995**	**154,84,79,864**

As per our report of even date
for M/s G. R. Venkatanarayana
Chartered Accountants
FRN 004616S

(C. S. R. Murthy)
Administrative Officer

(Ravi Subrahmanyan)
Director

(G. R. Venkatanarayana)
Partner
M No. 018067
M/s. G.R. VENKATANARAYANA
Chartered Accountants
618, 75th Cross, 6th Block,
Rajajinagar, BANGALORE-560 010

BANGALORE / 22/07/2016

RAMAN RESEARCH INSTITUTE, BANGALORE
INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR ENDED 31ST MARCH 2016

(Amount in INR)

INCOME	Schedule	Current Year	Previous Year
Income from Sales/Services	12	-	-
Grants/Subsidies	13	28,35,45,000	29,76,43,413
Fee/Subscriptions	14	-	-
Income from Investments for earmarked/endowment funds)	15	-	-
Income from Royalty	16	-	-
Interest Earned	17	26,55,199	-
Other Income	18	13,90,541	14,17,500
Increase/Decrease in stock of finished goods	19	-	-
TOTAL (A)		**28,75,90,740**	**29,90,60,913**
EXPENDITURE			
Establishment Expenses	20	20,54,97,570	20,01,99,744
Other Administrative Expenses	21	10,52,30,559	11,08,00,762
Expendtiture on Grants/Subsidies	22	-	-
Interest	23	-	-
Depreciation (Net as per Schedule 8)		5,58,51,498	-
TOTAL (B)		**36,65,79,627**	**31,10,00,506**
Balance being excess of expenditure over income (A-B)		(7,89,88,887)	(1,19,39,593)
Transfer to Capital Fund -Creation of Capital Assets		(5,58,51,498)	-
Transfer to Capital Fund -Grant Balance (Recurring Grant)		(2,31,37,389)	-
BALANCE BEING SURPLUS/(DEFICIT) CARRIED TO CORPUS/CAPITAL FUND		**(7,89,88,887)**	**(1,19,39,593)**
Significant Accounting Policies	24		
Contingent Liabilities and Notes on Accounts	25		

As per our report of even date
for M/s G. R. Venkatanarayana
Chartered Accountants
FRN 004616S

(C. S. R. Murthy)
Administrative Officer

(Ravi Subrahmanyan)
Director

(G. R. Venkatanarayana)
Partner
M No. 018067

M/s. G.R. VENKATANARAYANA
Chartered Accountants
618, 75th Cross, 6th Block,
Rajajinagar, BANGALORE-560 010

BANGALORE / 22/07/2016

RAMAN RESEARCH INSTITUTE, BANGALORE
RECEIPTS AND PAYMENTS STATEMENT FOR THE YEAR ENDED 31ST MARCH 2016

(Amount in INR)

RECEIPTS	Current Year	Previous Year	PAYMENTS	Current Year	Previous Year
I. Opening Balances			**I. Expenses**		
a) Cash in hand	-	-	a) Establishment Exp	17,51,74,919	20,39,70,500
b) Bank Balances			b) Admin Expenses	3,77,76,101	10,51,27,292
i) in current accounts	76,48,639	41,14,283			
ii) in deposit accounts	-	-	**II. Payments made against projects**	10,02,322	47,37,235
iii) in savings accounts	-	-	**III. Investments made**		
iv) in Stamps (Franking M/C)	19,093	285	a) Out of Earmarked/End. Funds	-	-
II. Grants Received			b) Out of own funds	-	-
a) From Govt. of India	35,27,00,000	32,83,11,004			
b) From State Govt.	-	-	**IV. Increase in Current Assets**	14,63,50,731	59,57,09,914
c) From other sources	-	1,00,000	**V. Capital Expenditure**		
			a) Purchase of fixed assets	4,66,59,592	5,76,70,963
III. Project Receipts		67,56,745	b) Expenditure on Work-in-progress	-	8,93,989
V. Increase in Current Liabilities	8,82,45,647	22,17,392	**VI. Refund of surplus money/Loans**		
VI. Decrease in Current Assets	14,15,17,670	65,57,21,766	a) To the Govt. of India	-	-
VII. Interest Received			b) To the State Govt.	-	-
a) On Bank deposits	27,04,444	-	c) To other providers of funds	-	-
b) on Loans, Advances etc.	3,65,585	-			
			VII. Finance Charges (Interest)		-
VIII. Other Income (Specify)	3,42,851	13,17,500	**VIII. Decrease in Current Liabilities**	16,17,77,714	4,07,39,429
IX. Amount Borrowed	-	1,79,78,079	**IX. Closing Balances:**		
X. Any other receipts	-	-	a) Cash in hand	2,092	-
			b) Bank Balances	1,47,28,657	76,48,639
			c) Deposits	1,00,46,575	-
			d) Stamps (Franking M/C)	25,226	19,093
TOTAL	**59,35,43,929**	**101,65,17,054**		**59,35,43,929**	**101,65,17,054**

(C. S. R. Murthy)
Administrative Officer

(Ravi Subrahmanyan)
Director

BANGALORE / 22/07/2016

As per our report of even date
for M/s G. R. Venkatanarayana
Chartered Accountants
FRN 004616S

(G. R. Venkatanarayana)
Partner
M No. 018067

M/s. G.R. VENKATANARAYANA
Chartered Accountants
618, 75th Cross, 6th Block,
Rajajinagar, BANGALORE-560 010

RAMAN RESEARCH INSTITUTE, BANGALORE

SCHEDULES FORMING PART OF BALANCE SHEET AS AT 31ST MARCH 2016

(Amount in INR)

Schedule 1- Corpus/Capital Fund		Current Year		Previous Year
(1) CAPITAL FUND REPRESENTING ASSETS CREATED OUT OF GRANTS				
As per last account	104,69,54,686		106,27,08,808	
Addition during the year	9,20,27,215		5,85,64,952	
Less: Deductions during the year *(includes WIP/Advances capitalised)*	5,22,64,179		71,72,125	
Less: Depreciation chargeable	5,58,51,498		6,71,46,949	
BALANCE AS AT THE YEAR END		103,08,66,224		104,69,54,686
(2) GRANT BALANCES				
(a) NON-RECURRING GRANT				
Balance as at the beginning of the year		(1,83,43,497)		95,53,864
Add: Contributions during the year	6,91,55,000		3,06,67,591	
Add: Interest earned on LC Margin Money & Term Deposits	6,40,465	6,97,95,465	-	3,06,67,591
Less: Expenditure incurred during the year		3,97,63,036		5,85,64,952
(Nett Addition-As per Schedule 8)				
BALANCE AS AT THE YEAR END		1,16,88,932		(1,83,43,497)
(b) RECURRING GRANT				
Balance as at the beginning of the year	(29,62,617)		89,76,976	
Transferred from Income & Expenditure-	(2,31,37,389)		(1,19,39,593)	
-Account for the year				
BALANCE AS AT THE YEAR END		(2,61,00,006)		(29,62,617)
TOTAL (1+2)		**101,64,55,150**		**102,56,48,572**

Schedule-2- Reserves & Surplus		Current Year		Previous Year
NOT APPLICABLE		-		-
TOTAL		**-**		**-**



RAMAN RESEARCH INSTITUTE, BANGALORE
SCHEDULES FORMING PART OF BALANCE SHEET AS AT 31ST MARCH 2016

Schedule 3- Earmarked/Endowment Funds

(Amount in INR)

Sl No	Project Name	Funding Agency	Opening Balance	Received during the year	Utilisation			Total Utilisation	Balance as on 31/03/16
					Capital Expenditure	Recurring Expenditure	Advances/ Receivables		
Funded by Government Agencies									
1	ISRO-Polix Project-Prof Biswajit	ISRO	(1,09,961)	44,48,000	-	-	-	-	43,38,039
2	DST-MWA Project- Prof Shiv Sethi	DST	36,269	-	-	-	-	-	36,269
3	Ramanujan Fellowship- Dr Pramod	DST	2,06,447	-	-	-	-	-	2,06,447
4	Indo-Aus BMWF Jt. Research	DST	70,579	-	-	-	-	-	70,579
5	Biomechanics of Synaptogesis-Dr Pramod	DBT	7,321	-	-	-	-	-	7,321
6	Bhatnagar Award-Prof. Madan Rao	CSIR	(5,40,000)	-	-	1,80,000	-	1,80,000	(7,20,000)
7	Indo-Aus Strategic Res. Fund- Dr Reji	DST	(4,820)	-	-	-	-	-	(4,820)
8	CEFIPRA Grant- Prof Hema R	IFCPAR	1,37,525	-	-	-	-	-	1,37,525
9	Sr. Research Fellowship-Karthik Sarkar	CSIR	(38,524)	-	-	-	-	-	(38,524)
10	Indo-Russia Joint Project- Prof Biman Nath	DST	4,73,600	-	-	-	-	-	4,73,600
11	Ramalingaswamy Fellowship- Dr. Gautam	DBT	72,801	18,60,000	-	17,34,967	-	17,34,967	1,97,834
12	Bhatnagar Award-Dr. Sadiq Rangwala	CSIR	-	2,25,000	-	2,25,000	-	2,25,000	-
13	Inspire Fellowship-Dr. Saurav Datta	SERB	-	19,00,000	-	9,63,749	-	9,63,749	9,36,251
14	CEFIPRA Grant- Dr. Sadiq Rangwala	IFCPAR	-	7,61,600	-	-	-	-	7,61,600
15	Bhatnagar Award-Prof Deshpande	CSIR	-	5,40,000	-	5,40,000	-	5,40,000	-
16	Inspire Fellowship-Dr. Dibyendu	SERB	-	17,80,000	-	4,20,467	-	4,20,467	13,59,533
	TOTAL		**3,11,237**	**1,15,14,600**	**-**	**40,64,183**	**-**	**40,64,183**	**77,61,654**
Funded by other than Government Agencies									
1	FQXi- Dr. Sumati Surya	FQXi	34,951	-	-	50,873	-	50,873	(15,922)
2	IAGRG Grant-Dr. Sumati Surya	IAGRG	-	50,000	-	49,098	-	49,098	902
	TOTAL		**34,951**	**50,000**	**-**	**99,971**	**-**	**99,971**	**(15,020)**
Retirement Funds									
1	Gratuity Fund	-	7,29,16,663	56,72,259	-	1,43,56,644	-	1,43,56,644	6,42,32,278
2	Leave Salary Fund	-	6,09,19,901	47,00,327	-	1,16,36,135	-	1,16,36,135	5,39,84,093
3	Pension Commutation Fund	-	18,21,18,375	1,51,47,375	-	1,24,48,220	-	1,24,48,220	18,48,17,530
4	RRI Pension Fund	-	6,39,15,281	2,17,72,148	-	-	2,22,16,185	2,22,16,185	6,34,71,244
5	RRI Provident Fund	-	10,88,10,675	82,28,093	-	-	2,75,300	2,75,300	11,67,63,468
	TOTAL		**48,86,80,895**	**5,55,20,202**	**-**	**3,84,40,999**	**2,24,91,485**	**6,09,32,484**	**48,32,68,613**
	GRAND TOTAL		**48,90,27,083**	**6,70,84,802**	**-**	**4,26,05,153**	**2,24,91,485**	**6,50,96,638**	**49,10,15,247**



RAMAN RESEARCH INSTITUTE, BANGALORE
SCHEDULES FORMING PART OF BALANCE SHEET AS AT 31ST MARCH 2016

(Amount in INR)

Schedule 4- Secured Loans & Borrowings	Current Year		Previous Year	
NOT APPLICABLE	-	-	-	-
TOTAL		-		-

Schedule-5- Unsecured Loans & Borrowings	Current Year		Previous Year	
NOT APPLICABLE	-	-	-	-
TOTAL		-		-

Schedule 6- Deferred Credit Liabilities	Current Year		Previous Year	
NOT APPLICABLE	-	-	-	-
TOTAL		-		-

Schedule-7- Current Liabilities & Provisions	Current Year		Previous Year	
A. CURRENT LIABLITIES				
1. Sundry Creditors				
a) for goods	6,38,256		2,11,703	
b) Others	1,09,53,391	1,15,91,647	1,33,86,278	1,35,97,981
2. Earnest Money Deposit		8,91,500		6,07,000
3. Statutory Liabilities				
a) Overdue				
b) Others	-			39,000
4. Other Current Liabilities (Incl. Security Deposit)	-	11,58,948		10,74,703
TOTAL (A)		1,36,42,095		1,53,18,684
B. PROVISIONS				
1. Gratuity	88,224		-	
2. Superannuation / Pension	19,78,279		1,84,85,525	
3. Accumulated Leave Encashment	-		-	
4. Others (Specify)	8,70,000		-	
TOTAL (B)		29,36,503		1,84,85,525
TOTAL (A+B)		**1,65,78,598**		**3,38,04,209**

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SCHEDULES FORMING PART OF BALANCE SHEET AS AT 31ST MARCH 2016

Schedule 8- Fixed Assets (Amount in INR)

Description	GROSS BLOCK					DEPRECIATION				NET BLOCK	
	Cost /Valuation as at the beginning of theyear	Additions During the year	Deductions during the year	Cost / Valuation at the end of the year	Rate	Cost /Valuation as at the beginning of theyear	Additions During the year	Deductions during the year	Cost / Valuation at the end of the year	As at the end of current year	As at the end of Previous Year
1. Land											
a) Freehold											
Malleshwaram	3,78,735	-	-	3,78,735	0.00	-	-	-	-	3,78,735	3,78,735
RMV II Stage	31,19,436	-	-	31,19,436	0.00	-	-	-	-	31,19,436	31,19,436
HMT Jalahalli	8,00,63,261	-	-	8,00,63,261	0.00	-	-	-	-	8,00,63,261	8,00,63,261
2. Buildings											
a) On freehold land	17,34,63,524	19,09,115	-	17,53,72,639	1.63	2,71,46,252	28,57,020	-	3,00,03,272	14,53,69,367	14,63,17,272
3. Canteen Infrastructure	42,76,021	-	-	42,76,021	4.75	10,15,555	2,03,111	-	12,18,666	30,57,355	32,60,466
4. Plant Machinery, Equipment	82,70,22,853	4,06,02,286	-	86,76,25,139	4.75	29,80,73,191	4,03,71,283	-	33,84,44,474	52,91,80,665	52,89,49,662
5. Vehicles	50,09,321	70,706	-	50,80,027	9.50	42,84,312	4,82,602	-	47,66,914	3,13,113	7,25,009
6. Furniture & Fixtures	1,37,00,220	5,19,221	-	1,42,19,441	6.33	72,82,222	8,92,261	-	81,74,483	60,44,958	64,17,998
8. Computer Peripherals	15,32,19,929	16,68,956	-	15,48,88,885	16.21	15,32,19,928	1,92,108	-	15,34,12,036	14,76,849	1
9. Library Books	22,79,59,116	6,07,290	-	22,85,66,406	4.75	10,02,80,614	1,08,53,113	-	11,11,33,727	11,74,32,679	12,76,78,502
CWIP/Advances for Capital Eqpt	3,84,50,524	4,66,49,641	5,22,64,179	3,28,35,986	0.00	-	-	-	-	3,28,35,986	3,84,50,524
TOTAL	**152,66,62,940**	**9,20,27,215**	**5,22,64,179**	**156,64,25,976**		**59,13,02,074**	**5,58,51,498**	**-**	**64,71,53,572**	**91,92,72,404**	**93,53,60,866**

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SCHEDULES FORMING PART OF BALANCE SHEET AS AT 31ST MARCH 2016

(Amount in INR)

Schedule 9- Investments from Earmarked/Endowment Funds	Current Year	Previous Year
1. In Fixed Deposits	-	-
RRI Pension Fund	5,42,41,228	5,66,18,214
RRI Provident Fund	10,63,63,549	9,45,30,517
2. Other Approved Securities	-	-
3. Shares	-	-
4. Debentures / Bonds	-	-
5. Subsidiaries and Joint Ventures	-	-
6. Retirement funds vested in SBI Life Insurance Limited	30,30,33,901	31,59,54,939
TOTAL	**46,36,38,678**	**46,71,03,670**

Schedule-10 Investment (Others)	Current Year	Previous Year
1. In Government Securities	-	-
2. Other Approved Securities	-	-
3. Shares	-	-
4. Debentures / Bonds	-	-
5. Subsidiaries and Joint Ventures	-	-
6. Others (Specify)-Fixed Deposits	1,00,46,575	-
TOTAL	**1,00,46,575**	**-**



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SCHEDULES FORMING PART OF BALANCE SHEET AS AT 31ST MARCH 2016

(Amount in INR)

Schedule 11- Current Assets, Loans & Advances	Current Year		Previous Year	
A. CURRENT ASSETS				
1. Inventories		14,61,442		10,06,416
2. Cash balances in hand (Including cash imprest)		2,092		-
3. Unused stamp value on Postal Franking Machine		25,226		19,093
4. Bank Balances				
Main Account				
On Current Accounts	1,40,15,603		2,31,38,912	
On Savings Bank Account	7,13,054	1,47,28,657	18,777	2,31,57,689
Pension Fund Account				
On Current Accounts	52,35,055		57,04,449	
On Savings Bank Account	29,14,559	81,49,614	5,27,477	62,31,926
Provident Fund Account				
On Current Accounts	47,57,979		1,15,38,690	
On Savings Bank Account	34,87,997	82,45,976	18,08,173	1,33,46,863
TOTAL (A)		3,26,13,007		4,37,61,987
B. LOANS/ADVANCES AND OTHER ASSETS				
1. Advances and other amounts recoverable in cash				
On Capital Account	8,89,61,800		8,89,61,800	
Deposits	33,21,706		34,67,761	
Others	29,04,011	9,51,87,517	33,02,965	9,57,32,526
2. Income Accrued				
Main Account	2,752		-	
Provident Fund Account	14,89,924		3,94,295	
Pension Fund Account	7,10,887	22,03,563	7,25,038	11,19,333
3. Claims Receivable				
Main Account	53,717		45,22,379	
Provident Fund Account	6,64,019		5,39,000	
Pension Fund Account	3,69,515	10,87,251	3,40,103	54,01,482
TOTAL (B)		9,84,78,331		10,22,53,341
TOTAL (A+B)		**13,10,91,338**		**14,60,15,328**

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RAMAN RESEARCH INSTITUTE, BANGALORE

SCHEDULES FORMING PART OF INCOME & EXPENDITURE ACCOUNT FOR THE YEAR ENDED 31ST MARCH 2016

(Amount in INR)

Schedule 12- Income from Sales/Service	Current Year	Previous Year
NOT APPLICABLE	-	-
Total	**-**	**-**

Schedule 13- Grants/Subsidies	Current Year	Previous Year
1. Central Government		
a) Non-Plan		
i) Grant-in-Aid	50,00,000	81,98,903
b) Plan		
i) Grant-in-Aid	27,85,45,000	28,94,44,510
Total	**28,35,45,000**	**29,76,43,413**

Schedule 14- Fees/Subscriptions	Current Year	Previous Year
NOT APPLICABLE	-	-
Total	**-**	**-**

Schedule 15- Income from Investments	Current Year	Previous Year
NOT APPLICABLE	-	-
Total	**-**	**-**

Schedule 16- Income from Royalty/Publication	Current Year	Previous Year
NOT APPLICABLE	-	-
Total	**-**	**-**

Schedule 17- Interest Earned	Current Year	Previous Year
1) On Term Deposits		
a) With scheduled banks	17,57,414	-
2) On Savings Accounts		
a) With Scheduled banks	3,09,317	-
3) On Loans/Advances		
a) Employees	5,88,468	-
Total	**26,55,199**	**-**

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SCHEDULES FORMING PART OF INCOME & EXPENDITURE ACCOUNT FOR THE YEAR ENDED 31ST MARCH 2016

(Amount in INR)

Schedule 18- Other Income	Current Year	Previous Year
1) Profit on sale/disposal of assets		
a) Own Assets	-	-
b) Assets acquired out of grants	-	-
2) Miscellaneous Income	13,90,541	14,17,500
Total	**13,90,541**	**14,17,500**

Schedule 19- Increase/(Decrease) in stock of finished goods	Current Year	Previous Year
NOT APPLICABLE	-	-
Total	-	-

Schedule 20- Establishment Expenses	Current Year	Previous Year
a) Salaries & Wages	7,92,60,114	6,93,19,771
b) Allowances & Bonus	8,81,71,728	9,44,65,513
c) Contrbution to Provident Fund	15,72,292	17,86,002
d) Contribution to NPS	20,79,245	16,53,501
e) Staff welfare expenditure	93,22,456	93,06,175
f) Retirement/Terminal benefits	2,50,91,735	2,36,68,782
Total	**20,54,97,570**	**20,01,99,744**

Schedule 21- Other administrative expenses	Current Year	Previous Year
1) Advertisement	1,95,302	1,98,795
2) Amenities	15,03,341	14,59,922
3) Audit Fee	1,12,700	47,191
4) Bank Charges	18,938	8,470
5) Campus Maintenance	97,97,486	77,53,650
6) Conveyance	5,22,573	4,05,707
7) Corporation Taxes	2,18,659	3,04,018
8) Creche	2,40,000	2,40,000
9) Electricity Charges	1,16,63,088	1,04,59,176



Schedule 21- Other administrative expenses (Continued)	Current Year	Previous Year
10) Entertainment & Hospitality	3,48,603	3,39,354
11) Freight	3,22,880	3,93,200
12) Honorarium & Professional Fee	50,41,217	18,70,472
13) Inter Institutional Collaboration	1,50,000	21,70,795
14) Journal Subscription	55,44,222	75,79,826
15) Lease Rent (Gauribidanur Land)	3,81,176	4,39,172
16) Miscellaneous Expenses	8,25,201	4,77,372
17) Outreach	3,04,197	1,59,399
18) Patent Fee	16,42,823	2,32,995
19) Payroll Processing Charges	3,65,983	3,21,631
20) Ph.D Programme Expenditure	19,53,264	41,91,188
21) Postage & Courier Charges	1,52,948	1,36,294
22) Printing & Stationery	2,60,986	12,89,339
23) Project Working Expenses	14,30,529	66,36,437
24) Repairs & Maintenance	76,13,731	92,70,442
25) Security	75,58,788	72,89,793
26) Seminar/Conference/Summer School	33,00,798	12,57,955
27) Stores & Consumables	2,25,18,886	2,57,58,099
28) Telephone & Communication Charges	19,40,390	25,31,681
29) Travel Expenditure	75,71,722	55,83,216
30) Uniform & Livery	2,10,547	2,28,993
31) University Affiliation Fee	9,00,000	3,00,000
32) Vehicle Maintenance/Transport	22,98,658	22,55,080
33) Visiting Students Programme	63,96,952	79,87,341
34) Wages	8,77,400	5,66,225
35) Water Charges	10,46,571	6,57,534
Total	**10,52,30,559**	**11,08,00,762**



RAMAN RESEARCH INSTITUTE, BANGALORE

Schedule-24

SIGNIFICANT ACCOUNTING POLICIES

1. Accounting Convention

The financial statements are prepared on historical cost convention. The Institute has switched over to mercantile system of accounting starting this financial year. This is necessitated on account of change in presentation of financial statement in accordance with the Uniform Accounting Format for Central Autonomous Organisations as prescribed by Controller General of Accounts, Govt. of India.

2. Fixed Assets

Fixed Assets are stated at cost of acquisition that includes inward freight, duties, taxes and incidental expense to bring the asset to use. To confirm with presentation in the new format, advance payments for procurement of capital assets have been shown in Schedule-8 (fixed assets) to the extent such advances have been actually paid. No depreciation is charged on such items. The same is shown as utilisation under Schedule-1 (Capital Fund). The asset value, stated in Schedule-8, is nett of depreciation.

3. Depreciation

Depreciation is charged on **STRAIGHT LINE BASIS** at the following rates

a. Buildings @ 1.63 %
b. Capital Equipment, Canteen Infrastructure and Books @ 4.75%
c. Computer & Peripherals @ 16.21%
d. Vehicles @ 9.50%

Depreciation is charged in the Income & Expenditure account on time proportionate basis and reduced from the Capital Fund. In respect of asset blocks that end with a book value less than Re 1/- on applying depreciation, the book balance is closed with a notional value of Re 1/- by limiting depreciation charged to the notional book value.

4. Inventory

Stock on hand, such as spares, stationery and consumables are valued at cost

5. Government Grants

Grants received from Department of Science & Technology, Govt. of India under Plan and Non-Plan is Accounted for as Core Grants.

Grants with specific sanction for recurring expenditure is shown under Income & Expenditure Account. Unspent balance, which is nett of expenditure incurred during the year, is reported in the balance sheet under Schedule 1 (Grant Balances-Recurring Grant).

Grants received for Creation of Capital Assets received during the year is added to the previous year's balance in the Balance Sheet. Unspent balance, which is nett of utilisation during the year, is shown under Schedule-1 (Grant Balances-Non Recurring Grant). Funds utilised to Create Capital Assets is shown as an addition in the Capital Fund as per AS-12.



		The Institute also receives Extra Mural Grants from various funding agencies. Such grants are shown as part of Schedule 3 (Earmarked / Endowment Funds).
6.	Foreign Currency Transactions	Transactions denominated in Foreign Currency are accounted for at the rates prevailing on the date of actual transaction. No provision is made to account for gains and losses arising out of exchange fluctuations.
7.	Retirement Benefits	The Institute's contribution to Provident Fund and Pension Fund are charged to Income & Expenditure Account. Deficit, if any, in the Provident Fund and Pension Account is being provided for in the books. There has been no deficit in Provident Fund Account this year

Schedule-25

CONTINGENT LIABILITIES AND NOTES ON ACCOUNTS

A. Contingent Liabilities

1.	Claims against the Institute not acknowledged as debt	NIL
2.	Bank guarantees given by the Institute	NIL
3.	Disputed demands in respect of taxes	NIL

B. Notes on Accounts

1.	Current Assets, Advances & Deposits	Current Assets, Advances and Deposits have a value on realisation in the ordinary course of activities. The extent of realisation is equal atleast to the aggregate amount appearing in the Balance Sheet
2.	Employees' Retirement Benefits	a. Institute's contribution to the Provident Fund account are charged to Income & Expenditure Account of the institute
		b. As prescribed by the Govt. of India, the Institute has subscribed to Pension funds vested in SBI Life Insurance Company Limited, in respect of quantifiable liabilities of service benefits like Gratuity and Cash equivalent of Earned Leave. The Institute has also covered its liabilities for Commuted Value of Pension, through funds vested in SBI Life Insurance Company Limited
		c. The amounts standing to the credit of the funds vested in SBI Life Insurance Company Limited are held in the name of the Institute in a fiduciary capacity. Balances appearing in the fund statements as at the close of financial year is shown under Schedule-3 (Earmarked/Endowment Funds-Retirement Funds). Interest earned, if any,

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during the year is treated as an Addition to the fund and reported accordingly in Schedule-3. Payouts on retirement on account of Gratuity, Cash equivalent of Earned Leave and Commutted value of Pension is through the fund.

d. In pursuance of the directions of the Council, the amount representing Institute's contribution to the CPF in respect of eligible Senior Scientific and Technical staff members (who joined the Institute before 01/01/2004) on contractual terms are allowed to exercise an option to opt for the Institute's pension scheme, on periodic renewal of their contracts for continuous engagement in the Institute upto superannuation. PF balances standing to the credit of such members is transferred to the Pension corpus. The income generated on the corpus is used to partially fund the pension liability. Deficit, if any, is met out of regular grants-in-aid.

e. Employees who have joined the Institute after 01/01/2004, are compulsorily enrolled under the New Pension Scheme

3. Advance for purchase of land

The Institute has deposited Rs. 8,89,61,800/- with M/s Hindustan Machine Tools Limited, being full value of a land, in pursuance of a sale agreement entered into between the Institute and HMT Limited on 13th March 2009. The conveyance deed is yet to be signed pending a formal approval from Government of India. It is to be noted that a part of this land is earmarked for Indian Academy of Sciences. The Academy has made a token remittance of Rs. 1,00,00,000/-. This is shown as part of Schedule 7 (A)-Sundry Creditors (for others) that forms part of the Balance Sheet. A matching current asset, in form of an investment, has been created in the books as shown in Schedule 10.

4. Schedules 1 to 25 are annexed to and form an integral part of the Balance Sheet as at 31st March 2016 and the Income & Expenditure Account for the year ended on that date.

5. Following the changeover in financial reporting as per Uniform Format of Accounts, numbers pertaining to the previous years have been regrouped and rearranged to conform to current year figures

As per our report of even date
For **G. R. Venkatnarayana**
Chartered Accountants
FRN 004616S

(C. S. R. Murthy)
Administrative Officer

(Ravi Subrahmanyan)
Director

(G. R. Venkatnarayana)
Partner
M. No. 018067

BANGALORE / 22/07/2016

M/s. G.R. VENKATANARAYANA
Chartered Accountants
618, 75th Cross, 6th Block,
Rajajinagar, BANGALORE-560 010







"The true wealth of a nation consists not in the stored- up gold but in the intellectual and physical strength of its people."


The Planet We Live On

