RAMAN RESEARCH INSTITUTE
BENGALURU



ANNUAL REPORT
2014 - 2015



Raman Research Institute, 2015
Annual Report: 2014 – 2015
Bengaluru, RRI.

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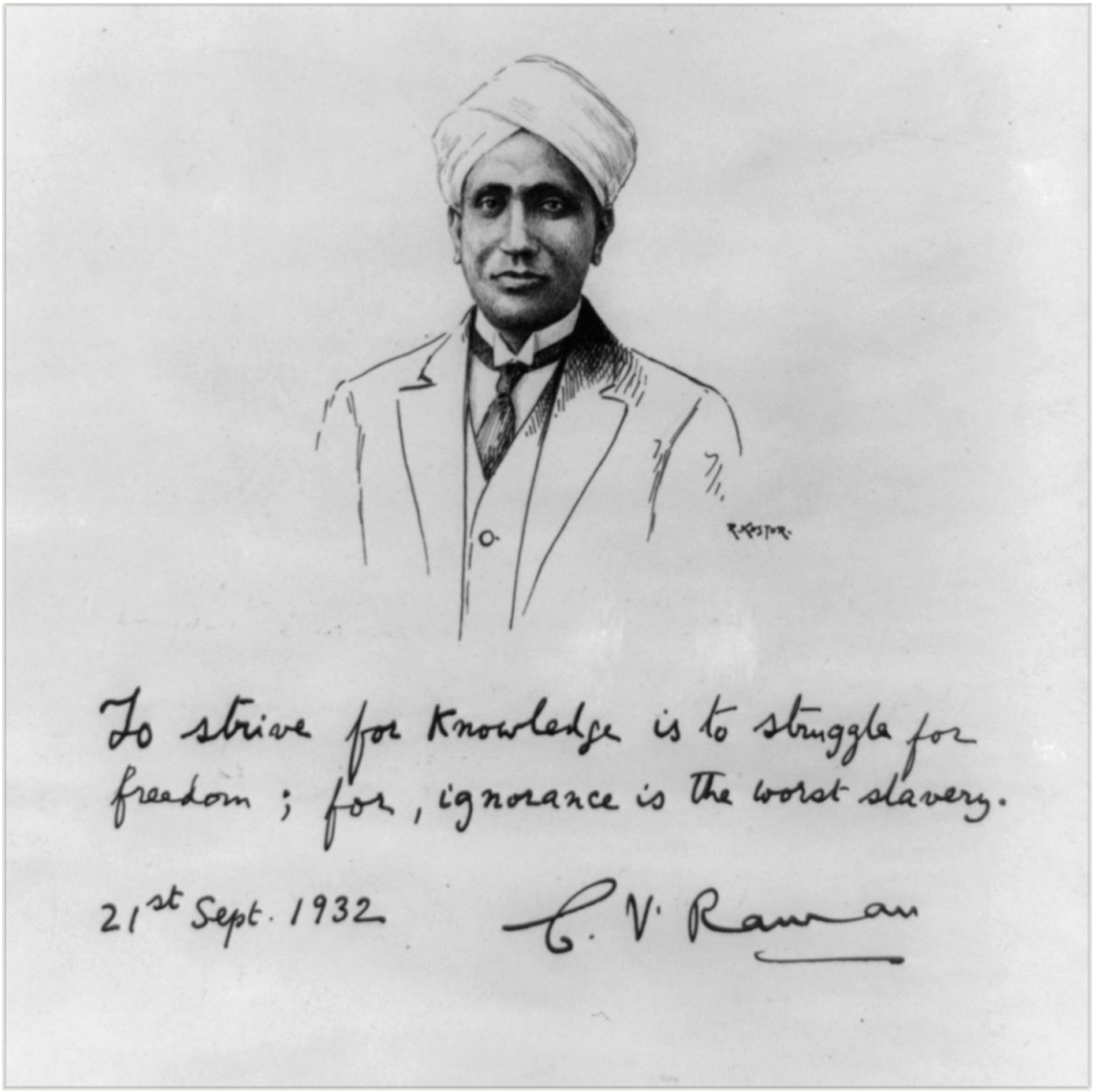




ANNUAL REPORT
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Raman Research Institute
Bengaluru


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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From the Director

The year 2014-15 saw continued excellence in theoretical, observational and experimental research at the Institute – in Astronomy & Astrophysics, Light & Matter Phyiscs, Soft Condensed Matter and Theoretcal Physics. This report provides a synopsis of the knowledge creation, knowledge transmission and other academic and outreach activities that the members of the Institute have engaged in.

A noteworthy recognition of the merit of research at RRI is the confernment of the Shanti Swarup Bhatnagar award for the year 2014 in Physical Sciences to Dr Sadiq Rangwala of RRI "for his outstanding contribution on collisionally cooled ions with trapped atoms leading to new ultracold ion-atom physics."

The last year saw new physicists of international repute accepting to be Adjunct Professors at RRI: Prof Kandasamy Subramanian from IUCAA, Pune, Prof Barry Sanders from IQC, Calgary, Prof Fabian Bretenaker from the National Center for Scientific Research, Orsay and Prof Satya Majumdar from the Laboratory for Theoretical Physics and Statistical Models, Orsay. They join Professors Rafael Sorkin of the Perimeter Institute, Calgary and M Muthukumar of the University of Massachussets, who have been happy to continue this association with RRI for a further three years. Adjunct Professors come to RRI for about a month a year and bring an international flavor and perspective to the academic atmosphere of the Institute.

RRI astronomy is poised to embark on a new adventure of exploration and discovery with India becoming a partner in the TMT project, which aims to build via an international effort a 30-m optical telescope on Mauna Kea, and India becoming a full member of the SKA: Square Kilometer Array radio telescope to be located across the continents of Australia and South Africa. RRI has joined an SKA-India consortium that coordinates the national effort towards effective participation in the radio astronomy.

The Institute ambience was enlivened by the happening of many events over the year. A Bangalore School on Statistical Physicswas held in April 2014, a Workshop on "Quantum Foundations and Information with a focus on the Quantum Measure and Coevent Formulation" was held in Jan 2015, the 28th meeting of the Indian Association for General Relativity and Gravitation (IAGRG) was held in March 2015, a Neighbourhood Astronomy Meeting was held in March 2015. These events are vital to our connectivity with the research community near and far, national institutions and the international body.

Ravi
Aug 11, 2015

At a Glance

Mission

The Raman Research Institute is engaged in research in basic sciences in the areas of Astronomy and Astrophysics, Light and Matter Physics, Soft Condensed Matter and Theoretical Physics. Through the years members of RRI have pursued research with the aim of creating knowledge and adding to the understanding and scientific comprehension of natural phenomena from sub-atomic to cosmological scales.

Director

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

Organization

RRI is an autonomous research institute. It is an institute that stands apart from all other research institutes in India by virtue of its rich history. The supreme body of RRI is the RRI Trust. The director is the chief executive and academic officer. Appointed by the RRI Trust by invitation, he exercises general supervision over the programmes and research projects of the institute. The Governing Council is responsible for the administration and management of the Raman Research Institute. Its members hold office for five-year terms. The Administrative Officer is responsible for the general administration of the Institute and represents it in legal and other related proceedings. The Governing Council appoints the Administrative Officer. The Finance Committee helps the Council with financial matters.

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

- Radio Astronomy Lab
- X-ray Astronomy
- Molecular Astronomy
- Cosmological Recombination & Reionization
- Strategic Developments in Radio Astronomy
- Light-Matter Interactions
- Laser Cooling & Quantum Optics
- Ultrafast and Nonlinear Optics
- Quantum Information & Computing
- Quantum Interactions
- 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:

- Physical Measurements 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. Library

4. Computer Facilities

Education

RRI offers the following academic programmes:

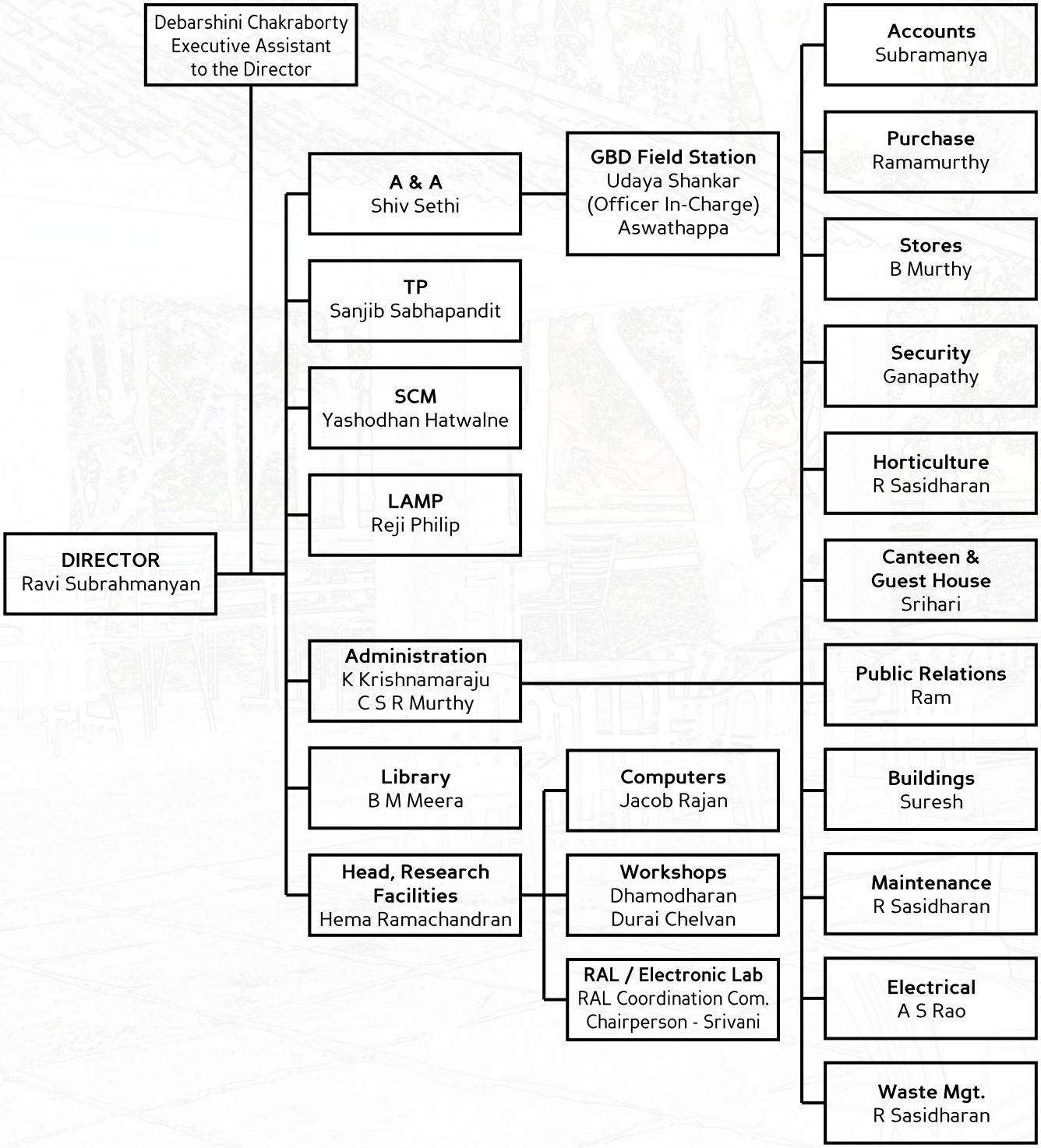
- PhD programme
- Postdoctoral Fellowship Programme
- Visiting Students Programme

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
Bangalore 560 080



Organisation

RRI Science Forum	: Gautam Soni, Andal Narayanan, Nayantara Gupta
Colloquia	: Joseph Samuel, Pramod Pullarkat, Sadiq Rangwala, Urbasi Sinha, Lakshminarayanan V.
Hostel Wardens	: Reji Philip, Arun Roy, B Ramesh, Urbasi Sinha
Admissions Coordinator	: Ranjini Bandyopadhyay, Biswajit Paul
SAAC	: VA Raghunathan (Chairperson), Sadiq Rangwala, Sumati Surya, Pramod Pullarkat, Shiv Sethi
In-House meeting	: PhD students – 3rd year
JAP Rep of RRI	: S Sridhar
Complaints Committee	: Srivani (Chairperson), Vrinda, K Raghunatha, Madan Rao, Mamatha Bai
Overseas Travel Commitee	: Udaya Shankar (Chairman), Biswajit Paul, Madan Rao
Evaluation Committee	: Dwarakanath K.S. (Chairman), Joseph Samuel, Biman Nath, VA Raghunathan, Sadiq Rangwala
Committee for Administration	: Sandeep Kumar (Chairperson), Hema Ramachandran, K Krishnamaraju, C.S.R. Murthy and Group Co-ordinators - Shiv Sethi, Reji Philip, Yashodhan Hatwalne, Sanjib Sabhapandit
Academics & Research Committee	: Joseph Samuel (Chairperson), Udaya Shankar , TN Ruckmongathan* / Hema Ramachandran
Coordinator of Visiting Students Programme	: Arun Roy
Library Committee	: Meera B.M. (Chairperson), Yashodhan Hatwalne, Supurna Sinha, Sadiq Rangwala, Nayantara Gupta
RRI Official Language Implementation Committee	: K. Krishnamaraju (Chairperson), CSR Murthy, PV Subramanya, R Ramesh, CN Ramamurthy, B Srinivasamurthy, BM Meera, M Manjunath, S R Ramasubramaniyan, CN Ganapathy, M Prema

* Till February, 2015

ASTRO PHYSICS AND ASTRO NOMY

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.

Theoretical Astrophysics

Cosmology

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. A recent major result in this field has been a dating of the formation epoch of cold dark matter in the universe as having occurred before a redshift of $z > 10^6$. Other fascinating questions being addressed in this field include factoring in primordial magnetic fields as possible sources of density perturbation in the early universe. It has been shown that magnetic fields as small as 0.1nG may have a significant impact on reionization history.

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 active galactic nuclei. During the period 2014-2015, several intriguing questions such as the origin of X-ray and Gamma ray emission in the large scale jet of quasar 3C 273, the origin of antiproton flux in the interactions of cosmic ray protons and nuclei with cold protons in Galactic sources to explain the PAMELA experiment results, and the reason behind the observed spectral cut-off in Gamma ray spectra from novae as detected by Fermi LAT, have been investigated and solutions proposed as research outcomes.

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 Sunyaev-Zeldovich distortion of the cosmic microwave background caused by the large amount of hot gas in the halos of massive galaxies, merging and collisions of multiple supernovae---exploding together at a single epoch or staggered in time---and the conditions under which they can give rise to galactic outflows, interaction of these

supernovae driven outflows from Milky Way type galaxies with the hot halo gas and the propagation dynamics and escape of ionizing photons from disk galaxies consistent with observed local UV background radiation and re-ionization of the universe.

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 instabilities, relaxation to equilibrium and fuelling of the BH, which contributes to its mass and spin.

Exoplanetary Dynamics

Most exoplanetary systems in binary stars are of S-type, consisting 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 remains largely unexplored. RRI has worked on presenting a mechanism that has the potential to explain several observed features of exoplanetary statistics.

Turbulent magnetic fields

The ionized gas in astrophysical bodies (stars, galaxies) is often differentially rotating and magnetized, with the magnetic field generated by electric currents in the highly conducting gas. Not only is the magnetic field strongly coupled to the gas, but it also acts back on the gas through Lorentz forces. Astronomical observations raise questions concerning the origin and growth of magnetic fields on large scales (dynamo action), and the organization of the field on small scales (turbulence). Some problems of interest are (a) dynamo action in turbulent shear flows, and (b) magneto-hydrodynamic turbulence.

Observational Astronomy

Observational cosmology

The last few decades have witnessed substantial progress in our understanding of the cosmological evolution of the universe as observations of the distant universe and evolution of the gas and galaxies has advanced to precision measurements of parameters that define the cosmology and parameters of structure formation. The cosmic microwave background is our vision of the universe as it was just 400,000 years into the expansion of the Big Bang model; this background has now been observed in exquisite detail both in spectral form and angular temperature variations in total intensity and polarization. The next decade or two is anticipated to be the era when we will explore the more complex and hence interesting evolution since the formation of the first stars and galaxies. RRI is a partner in the Murchison Widefield Array (MWA), which is a precursor to the SKA, in which again RRI is committed to participate as part of the SKA-India consortium.

This year, data from the Murchison Widefield Array observations have been analysed for detection of redshifted 21-cm from the Epoch of Reionization (EoR); additionally, a new method has been proposed for the detection of this signal using drift scan

strategy. Substantial progress has been made in the development of systems for detection of the global EoR signal, and in the coming year this is to be deployed in remote sites for science data. The first step in the building of a system for detecting recombination lines from cosmological recombination has also been taken: an analysis of the feasibility of such a detection from the ground has been done, an optimum frequency range identified, analysis methods defined, simulations performed to demonstrate that foregrounds can in principle be separated.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 is capable of describing the foreground spectrum and distinguishing the complex signal of interest.

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, 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 2014-2015, Murchison Widefield Array observations of the Abell 3667 have been analysed by the A&A group at RRI.

Pulsars

Pulsars are rapidly spinning high-magnetic-field neutron stars that originate in supernovae. They emit pulsed radio waves, X-rays and Gamma rays. 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. Studies on timing and spectral characterisation, orbital evolution, apsidal advance and orbital reprocessing of emitted X-rays are being conducted on pulsars of various types. Detection of off-pulse radio emission from pulsars and studies of the dependence of the shape of the emission beam on emission height and distance from the magnetic pole, which in turn affects the intrinsic circular polarization in pulsar emission, is being pursued.

Lifecycles of radio galaxies

A particular type of galaxy called the restarting radio galaxy was first discovered by astronomers of the Institute and has been their research interest for two decades. It is believed that activity in the nucleus of the galaxy had stopped and then restarted again afresh in multiple epochs. Using increasingly sensitive and high resolution radio telescopes it has now become possible to address questions like why the central engine ceased activity, how long it was dead before activity restarted, what mechanisms triggered a rebirth and so on. Astronomers at RRI are working on these questions together with other international collaborators.

Radio Galaxy Morphologies

Amongst the population of radio galaxies it is the X-shaped radio galaxy in particular, with its two typical lobes accompanied by two others shaped like the letter X, which 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 the 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 the various existing theories on the shape and structure of X-shaped radio galaxies. During the period 2014-2015, work was done to characterize the morphologies of radio galaxies in a unique sample of 52 radio galaxies selected for their low axial ratios. Based on the image analysis, three main types of 'distortions' to radio galaxy morphologies were isolated. A fraction of these source morphologies are suggested as generated by binary black hole mergers, which has been used to constrain the expectation for the gravitational wave background arising from coalescence of supermassive black holes.

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. Recently Suzaku studies of a pulsar that belongs to the class of highly absorbed supergiant high-mass X-ray binary (HMXB), which is characterized by a very high column density of absorbing matter, have been undertaken by this group. The upcoming 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.

Giant Radio Galaxies

Giant radio galaxies (GRGs) typically have lobes or plumes extending to megaparsec scales implying a timescale for growth of the order of tens to hundreds of millions of years. A major research project carried out and completed in the last year has been regarding GRGs and their unique relationship with their environments, both at local and global scales. This work on GRGs and their environments is aimed at the larger goal

of using GRGs to reveal the nature of the elusive warm-hot intergalactic medium (WHIM) in their vicinity. The comprehensive study undertaken by the RRI group in conjunction with universities in Australia has led to a possible characterization of the conditions under which they grow to giant sizes.

Radio and X-Ray Telescopes

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 frequency range of interest for many next generation radio telescopes to less than a GHz, with 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 an Indian Sky Watch 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 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 already begun gathering weak radio signals from deep space that are being analysed by astronomers at RRI and in the US and Australia. The data is expected to provide an insight into the dramatic evolution experienced by primordial cosmic gas as the first stars and galaxies formed in the early universe. That is a challenging goal and continued progress has been made towards this key science goal in the year gone by, with critical participation by RRI. Besides this, MWA data is helping study 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, and numerous collaborative publications have appeared during the year gone by.

Gauribadanur Radio Telescope (GRT)

This decametre wave radio telescope at Gauribadanur is operated in collaboration with the Indian Institute of Astrophysics. Operating at 34.5 MHz, this meridian-transit instrument has some tracking capabilities. It consists of 1000 fat 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 N-S arm of the beam can be tilted within a declination range of -45° to 75° while 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 build models for the emission regions at the polar caps of pulsars. They infer the astrophysics of this phenomenon using the GRT.

X-ray polarimeter (POLIX)

Anisotropy in the Thomson scattering of polarised X-rays is used to measure the degree and angle of linear polarisation of cosmic X-rays. 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-raypolarisationmeasurementis an asyetunexploredarea.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 is well along the road towards being launched into space in collaboration with ISRO. A laboratory model 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, processing electronics, housekeeping electronics and the design of a photo-electron polarimeter.

Based on the development that has been achieved in this project and the research potential, a committee has been constituted by the Programme Director of the Small Satellite Programme at ISRO to configure a small satellite mission.

Apart from POLIX, preliminary investigations for development of a X-ray pulsar based interplanetary navigation system are also underway. The advantages of such an instrument over currently used techniques would be its position independence and autonomous operation. Stability profiles of two sources are now being observed extensively for this purpose.

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 to be 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. Work has been done on the timing and spectral calibration of the Astrosat-LAXPC instrument and a software design for LAXPC data reduction is currently under development. 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.

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 its 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. For this purpose, a Ku-band receiver chain is also being built, including low-noise amplifiers, covering the 7-14 GHz range. Recently, another novel method has been proposed that enables single dishes to add short-spacing data to synthesis instruments. This method also allows for accurate measurement of surface deviations of antennas. 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 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.

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 helps the astronomer 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 30-200 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 systematics within the receiver used and also by the 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 relict radiation 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 2014-15 RRI has carried out a feasibility study for an experimental detection of these recombination lines and begun the system design and fabrication of a prototype spectral radiometer in the 2-6 GHz band for the detection.

SWAN (Indian Sky Watch 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 2014-15 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). Once this setup is fully developed and tested at Gauribidanur field station, relocation of the system at 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 as 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 2015. Active participation from students in all aspects of the SWAN, including studies of astronomical sources, will be sought and explicitly encouraged/supported.

Ongoing Research

Ramesh Balasubramanyam has research interests in the fields of Diffuse matter (atomic, molecular & ionised) in our and other galaxies, analog & digital signal processing, instrumentation and techniques for astronomy.

His research activities during the period 2014-2015 can be broadly categorized into two major themes, that of instrumentation and techniques for astronomy and signal processing. Under the first theme of instrumentation and techniques, two of his major projects consisted of the design of "An Efficient Linear Array Imager for Radio Astronomy" (RB, 2014, MNRAS 444, 2212), and "One Element Interferometer" (RB, 2014, MNRAS 444, 2128). Optical telescopes have large format CCD detectors at their foci and thereby image the skies rapidly. At low frequencies, telescopes have large primary beams and use synthesis method to image large areas quickly. At millimeterwave frequencies, primary beams are small even for small telescopes and detector arrays have modest sizes covering only small regions, unsuitable for quick imaging of large areas. Besides, synthesis arrays lack short spacing response, which becomes especially acute at higher frequencies, making them unsuitable for surveys of diffuse, distributed gas. In the last couple of years, Ramesh has been trying to address these two issues:

(a) How can survey speeds for molecular astronomy be improved? and

(b) How can short spacing response of millimeterwave array telescopes be enhanced?

In An Efficient Linear Array Imager for Radio Astronomy (RB, 2014, MNRAS 444, 2212), Ramesh has presented an optical scheme that makes two sets of orthogonal fan beams on the sky that can be cross-correlated to make a large instantaneous map. He shows that it improves the survey speed by a factor of $\sqrt{2}$ compared to other ways of deploying the same number of receivers. This will especially make large area surveys viable at millimeter waves. In the above cross-telescope, Ramesh has used two fan-beam telescopes (FBTs) in cross configuration. In this background, studying the off-axis performance of the fan-beam telescope has become important. Earlier, the group had carried out ray-tracing investigation for a Cassegrain FBT and found the results to be encouraging. They are now extending this study to include physical optics simulations.

In One Element Interferometer (RB, 2014, MNRAS 444, 2128), Ramesh has adapted Ryle's phase switching technique to a single dish fitted with either coherent or incoherent receivers to make correlation measurements possible. This method has been termed sub-aperture interferometry because it divides the aperture into two complementary sub-apertures and measures the correlation between the fields received from the two sub-apertures at the focus. This means one can make reliable continuum surveys with single dishes. In addition, as a synthesis array element such a telescope will add short spacing data so vital to image large scale smoothly distributed emission, especially at millimeterwaves.

Recently, Ramesh has also applied the principle of sub-aperture interferometry to measure surface deviations of a radiotelescope. This method has many advantages over other traditional methods such as radio-holography and photogrammetry and can be faster than them under typical conditions. It can use celestial

sources and measure surface deviations at different elevations. It promises to be robust against tracking errors. A report on this work is under preparation to be communicated to a journal shortly.

With the larger goal of demonstrating the concept behind a fan-beam telescope, Ramesh and Aditya P. (Visiting Student, RRI) are also building a unit that can operate in the Ku-band (6-16 GHz). To set its surface to 1 mm accuracy, they have built a Coordinate Measuring Machine using a commercially available Laser Distance Meter (Fluke D416). They have made a mount that allows the LDM to be moved in two orthogonal directions about a point, the third axis being the laser direction.
It has been mounted on the top of the fabrication shed and they will soon set the telescope surface using it. This work will be reported in a journal shortly.

Under the second theme of signal processing Ramesh has been engaged in a major piece of work involving Forward error correcting codes (FECCs) with Parvathi Chandrasekaran, (Research Assistant, RRI). FECCs use redundancy to detect and correct errors that occur in information storage, retrieval or transport. These are used in wireless and wireline digital communication as well as data storage and retrieval. Studying the efficacy of different codes under different situations and improving the effciency of coding and decoding is an essential approach in this signal-processing domain. These are relevant for synthesis arrays such as SKA, which will generate vast amounts of data that need to be communicated from the widely distributed elements to the central processing unit at high speeds, stored and retrieved. High data rate wireless communication is also essential for other modern applications. Inter Symbol Interference (ISI) and frequency selective fading caused by multi-path propagation hinders this. These problems can, however, be mitigated with Orthogonal Frequency Division Multiplexing (OFDM) and Multi-Input Multi-Output (MIMO) antenna system. Existing studies analyse the performance of different FECCs but none focus on a systematic analysis of them using a common link configuration. In a recent simulation study (PC & RB, 2014, IETE-JoR, 61(1), 56-64), Ramesh has filled this gap by using a common MIMO-STBC-OFDM communication link, transferring data at a base rate of 100 Mbps. They analyse 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.

Currently, they are extending this work to include Block Product Codes. These are multi-dimensional 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. Even though thus far they have used hard-decision approach to detect and correct errors, they are now working to implement soft decoding that should improve the performance further.

India has 27 million people with various disabilities. Of them, 6 million suffer locomotive disability. Therefore, it is socially relevant to make robust, reliable, economical and power-efficient devices that can help improve the quality of their lives. Paralysed or limb-impaired patients actually depend on assistance from others to carry out their normal daily personal activities. This is both costly (tying up of another person's time) and affects the self-esteem of the patients. Dependable motorised wheelchairs solve this problem to a large extent, at least within the confines of their homes. In cases where the patients are unable to operate the joystick,

voice-based driving of the wheelchair is necessary. Hardware voice recognition solutions exist, but of limited accuracy and vocabulary. Software solutions are reliable and scalable. Advances in the computing power of mobile devices and the availability of reliable, open source speech recognition engines such as Pocketsphinx has prompted Ramesh and his collaborators, Junaid Ahmed, (Project Engineer, RAL, RRI), Arasi Satya murthy, (RAL, RRI) to develop a reliable, rugged and economical Open-source Voice Command Interface Kit. They have designed its architecture, both hardware and software, the latter built as a lightweight framework, making it adaptable to any voice based application with ease and speed. To test its prowess, they have applied the Kit to voice-drive a motorised wheelchair. Recently, the group has submitted an article that describes the Kit, its wheelchair application and the results (JA, AS, RB 2015, under review with IEEE Transactions on Human-Machine Systems).

Autonomous feeding robotic arm is another such device of social relevance as a developing aid for limb-impaired patients in India. Ramesh and Prem J., (Visiting Student, RRI), Aadaleesan P., (SASTRA University, Tanjore) have developed a robotic arm with 5 degrees of freedom using the services of MES, RRI and have carried out its inverse kinematic and dynamic analysis with a view to driving it autonomously. They are in the process of adding object recognition and visual feedback to make it autonomous. This will also be reported in a journal once the device is functional.

Avinash Deshpande's activities are in Radio Astronomy, Signal & Image processing, Radio Transients and Pulsars, Polarization and Instrumentation, with an interest also in the detection of global signature of EoR.

During the year gone by, he has studied the detection of off-pulse radio emission from pulsars in collaboration with Kumar Raviranjan (PhD student, RRI). A pulsed nature of emission (as against continuous emission) is at the defining attribute of pulsars. Their average intensities, if they were to manifest as continuous emission, in most cases are too weak to be detectable, in presence of possible confusion from other continuous sources. The pulsed emission has been studied in great detail, and has lead to our present understanding of the physical picture of pulsars. However, the question as to whether pulsar radiation indeed has any intrinsic continuous component, in addition to its distinguishing pulsed signature, or if the periodic emission extends beyond the main/inter-pulse windows, have been issues of much interest since the early days of pulsar studies. *Huguenin et al.* (1971) and Perry, Lyne (1985) attempted to detect the so-called off-pulse/unpulsed/steady component of the pulsar emission, and had discussed implications for the general picture of pulsars. More recently, *Basu et al.* (2011) have reported detection of off-pulse emission from two long-period pulsars using the GMRT, which have raised issues regarding the nature of off-pulse emission, where and how it might originate and possible emission mechanism etc. (*Basu et al.* 2012). In this work, Deshpande has asked if any non-ideality in the measuring system could result in apparent off-pulse emission signature that would pass the criteria used so far to attribute its origin to pulsar. Through simulations they have been able to show that extended out-of-band leakage via aliasing could result in proportional contribution in the off-pulse regions, and increasingly so for higher DM pulsars.

Along with Karishma Bansal (IISER, Pune) Deshpande has also extracted the dynamic spectra from RRI-GBT MBR data. With a view to studying scintillation

characteristics as a function of frequency, a suitable processing pipeline has been developed to obtain total intensity dynamic spectra. This involved correcting the effects of gain compression, carefully identifying and excising radio-frequency interference, and providing optimal smoothing. The plan is for such spectra to now be obtained across the various bands of MBR, which together are expected to provide a yet untapped dimension in scintillation studies.

It was shown by Radhakrishnan and Rankin (1990) that intrinsic circular polarization in pulsars depends on the shape of the emission beam. To assess the expectation for evolution of the amount of circular polarization with frequency, Deshpande and Maria Kuruvilla (Visiting student, RRI) have theoretically estimated the possible modification in the shape of a sub-beam as a function of emission height, as well as distance from magnetic pole. They find that sub-beam shapes do change with height, but the estimated changes appear rather small, at least in the range of heights they have considered. This has important implications for the intrinsic circular polarization in pulsars.

In continued pursuit of reliable instrumental polarization calibration, Wasim Raja (RRI, Cotton College University, Guwahati) and Deshpande have together explored a few potential non-conventional techniques for polarization-calibration of radio astronomy instruments. They proposed an elegant Fourier-based method applicable for new generation telescopes that are being designed with an additional degree of freedom viz. rotation about the dish or feed axis. They also explored and showed usefulness of circularly polarized signals in characterizing certain instrumental parameters. Occurrence of pure circular states in the ultra short-time duration (nanoseconds) seen in Crab giant pulses are drawn attention to for their usefulness in instrumental calibration, in particular, the band-pass calibration.

In collaboration with Nishant Singh (JAP Student, RRI & Nordita, Sweden), Deshpande has explored the dynamics of stellar wind in a Roche potential: implications for outflows & periodicities relevant to astronomical masers, and generation of baroclinicity. They have studied the dynamics of stellar wind from one of the bodies in the binary system, where the other body interacts only gravitationally. More specifically,

(i) They explore the origin of observed periodic variations in maser intensity;
(ii) They address the nature of bipolar molecular outflows; and
(iii) They show generation of baroclinicity in the same model setup.

From direct numerical simulations and further numerical modelling, they find that the maser intensity along a given line of sight varies periodically due to periodic modulation of material density. This modulation period is of the order of the binary period. Another feature of this model is that the velocity structure of the flow remains unchanged with time in late stages of wind evolution. Therefore the location of the masing spot along the chosen sight line stays at the same spatial location, thus naturally explaining the observational fact. This also gives an appearance of bipolar nature in the standard position-velocity diagram, as has been observed in a number of molecular outflows, although there are other well understood situations responsible for most of the out-flows. Remarkably, they also find the generation of baroclinicity in the flow around binary system, offering another site where the seed magnetic fields could be generated due to the Biermann battery mechanisms, within galaxies.

Another of Deshpande's major pursuits during 2014-2015 consists of the fast-transient detection pipelines for GALFACTS survey data. A concerted effort by Tapasi Ghosh, Chris Salter (Arecibo Observatory, NAIC, Puerto Rico, USA) and Deshpande is being made 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 assess readily the possible astronomical origin of any detected dispersed single pulses during the search. Earlier pipelines could process only one beam data at a time. The new pipeline will be tested soon.

Deshpande's experimental work in electronics involves suitable modifications in the RRI-GBT MBR receiver backend (recalled from Green Bank), which is being configured presently for use for SWAN Phase-0, along with 8-tiles of MWA.

K.S. Dwarakanath's major research interests are in the areas of groups and clusters of Galaxies and in investigating the HI line at high z.

During the past academic year, his research activities mainly focused on the following problems-

(i) Study of Redshifted HI 21 cm-line from the Epoch of Reionization withDrift Scan,
(ii) The First Murchison Widefield Array low-frequency radio observations of cluster scale non-thermal emission: the case of Abell 3667 and
(iii) The Low-Frequency Environment of the Murchison Widefield Array: Radio-Frequency Interference Analysis and Mitigation

Detection of the epoch of reionization (EoR) in the redshifted HI 21 cm line is a challenging task. In this piece of work Dwarakanath and his collaborators have formulated the detection of the EoR signal using the drift scan strategy. This method potentially has better instrumental stability compared to the case where a single patch of sky is tracked. They demonstrated that the correlation time between measured visibilities could extend up to 1-2 hr for an interferometer array such as the Murchison Widefield Array, which has a wide primary beam. They have estimated the EoR power based on a cross-correlation of visibilities over time and shown that the drift scan strategy is capable of detecting the EoR signal with a signal to noise that is comparable/better compared to the tracking case. They have also estimated the visibility correlation for a set of bright point sources and argued that the statistical inhomogeneity of bright point sources might allow their separation from the EoR signal *(Paul et al. 2014)*.

The first Murchison Widefield Array observations of the well-known cluster of galaxies Abell 3667 (A3667) between 105 and 241 MHz have been analyzed in this study. A3667 is one of the best known examples of a galaxy cluster hosting a double radio relic and has been reported to contain a faint radio halo and bridge. The origin of radio haloes, relics and bridges is still unclear, however galaxy cluster merger seems to be an important factor. Dwarakanath along with Hindson et al have clearly detected the north-west (NW) and south-east radio relics in A3667 and find an integrated flux density at 149 MHz of 28.1 1.7 and 2.4 0.1 Jy, respectively, with an average spectral index, between 120 and 1400 MHz, of -0.9 0.1 for both relics. They find evidence of a spatial variation in the spectral index across the NW relic steepening towards the centre of the cluster, which indicates an ageing electron population. These properties are consistent with higher frequency observations. Their detected emission could be associated with a radio halo and bridge. However, due to the

presence of poorly sampled large-scale Galactic emission and blended point sources they were unable to verify the exact nature of these features during this investigation. *(Hindson et al 2014)*.

The Murchison Widefield Array is a new low-frequency interferometric radio telescope built in Western Australia at one of the locations of the future Square Kilometre Array. Dwarakanath, working with Offringa *et al* have described the automated radio-frequency interference detection strategy implemented for the Murchison Widefield Array, which is based on the aoflagger platform, and presented 72-231 MHz radio-frequency interference statistics from 10 observing nights. Radio-frequency interference detection removes 1.1 % of the data. Radio-frequency interference from digital TV was observed 3 % of the time due to occasional ionospheric or atmospheric propagation. After radio-frequency interference detection and excision, almost all data could be calibrated and imaged without further radio-frequency interference mitigation efforts, including observations within the FM and digital TV bands. The results were compared to a previously published Low-Frequency Array radio-frequency interference survey. The remote location of the Murchison Widefield Array has resulted in a substantially cleaner radio-frequency interference environment compared to Low-Frequency Array's radio environment, but adequate detection of radio-frequency interference is still required before data can be analysed. In this work, the group has also included specific recommendations designed to make the Square Kilometre Array more robust to radio-frequency interference, including: the availability of sufficient computing power for radio-frequency interference detection; accounting for radio-frequency interference in the receiver design; a smooth band-pass response; and the capability of radio-frequency interference detection at high time and frequency resolution (second and kHz-scale respectively) *(Offringa et al. 2015)*.

Nayantara Gupta's areas of current professional research interests are cosmic rays, neutrinos, gamma rays and gamma ray bursts. During the period of this annual report, her research has covered broadly four themes –

i) Possible Proton Synchrotron Origin of X-Ray & Gamma Ray Emission in Large Scale Jet of 3C 273in collaboration with Esha Kundu (Oskar Klein Centre, Stockholm University) (this work has been published in MNRAS Letters)
ii) Cosmic Ray Antiprotons from Nearby Cosmic Accelerators in collaboration with Jagdish Joshi (PhD student, RRI) (Published in Astro particle Physics)
iii) Very High Energy Antineutrinos from Photo-disintegration of Heavy Nuclei Near the Galactic Plane and iv) Origin of Spectral Cut-offs in the Gamma Ray Spectra from Novae.

The large scale jet of quasar 3C 273 has been observed between radio frequencies to γ ray frequencies. Earlier the X-ray emission from knot A of this jet has been explained with inverse Compton scattering of the cosmic microwave background radiations by the shock accelerated relativistic electrons in the jet. More recently it has been shown that this mechanism overproduces the gamma rayflux at GeV energy and violates the observational results from Fermi LAT. Nayantara and her collaborator have considered the synchrotron emission from a broken power law spectrum of accelerated protons in the jet to explain the observed X-ray to γ ray flux from knot A. The two scenarios discussed in their work are when

(a) Magnetic field is high, synchrotron energy loss time of the protons is shorter than

their escape time from the knot region and the age of the jet and (b) when their escape time is shorter than their synchrotron energy loss time and the age of the jet. These scenarios can explain the observed photon spectrum well for moderate values of Doppler factor. The required jet luminosity is high ~10^{46} erg / sec in the first scenario and moderate 10^{45} erg / sec in the second, which makes the second scenario more favourable.

The antiproton flux measured by PAMELA experiment might have originated from Galactic sources of cosmic rays. It is expected that these antiprotons will be produced in the interactions of cosmic ray protons and nuclei with cold protons. Gamma rays are also produced in similar interactions inside some of the cosmic accelerators. Nayantara and Jagdish have considered a few nearby supernova remnants observed by Fermi LAT. Many of them are associated with molecular clouds. Gamma rays have been detected from these sources, which most likely originate in decay of neutral pions produced in hadronic interactions. The observed gamma ray fluxes from these SNRs are used to find out their contributions to the observed diffuse cosmic ray antiproton flux near the earth.

The photo disintegration of cosmic ray nuclei by starlight leads to the production of secondary antineutrinos and gamma rays. In this work, Nayantara has calculated the antineutrino flux produced in this way from ultrahigh energy cosmic ray nuclei trapped close to the Galac- tic plane where the radiation field is intense. The IceCube detector has measured the neutrino / antineutrino flux in the TeV-PeV energy range. The calculated secondary antineutrino flux in the energy range of 10-100 TeV is found to be much less compared to the flux detected by the IceCube collaboration.

Fermi LAT has detected gamma rays of energy more than 100 MeV from four novae. These gamma ray transients have similar light curves. The detection of non-thermal variable fluxes of gamma rays implies cosmic ray acceleration in a wind driven medium inside these sources. Their gamma ray spectra are attenuated near a few GeV energy. In this work Nayantara has questioned whether these spectral cut-offs are due to the internal optical depths of pair production or the maximum energies of the shock accelerated electrons and protons, which radiate the gamma rays. Assuming simple power law spectra of shock accelerated electrons and protons she has fitted the observed spectrum from V407 Cyg 2010 in the leptonic and hadronic models. The results show that the observed spectral cut-offs could have their origin in pair production of gamma rays in the radiation field of the wind medium inside novae.

Biman B. Nath's areas of current research interests lie pre-dominantly in studies of interaction of diffuse gas with galaxies, galactic outflows, cosmic rays and intra cluster medium.

During the period of this annual report, Biman's research has broadly covered the following themes –

i) Fragmentation of primordial gas
ii) Interaction of galactic outflows with hot halo gas
iii) Sunyaev-Zeldovich effect of circumgalactic gas
iv) Evolution of multiple supernovae and
v) Escape of ionizing photons from disk galaxies

The fragmentation of primordial gas is crucial for the formation of first stars in the universe. However, a crucial reaction in this process is the 3-body H_2 formation rate, which

remains uncertain. In collaboration with Jayanta Dutta (University of Heidelberg, Germany), Paul C. Clark (Cardiff University, UK) and Ralf S. Klessen (University of Heidelberg, Germany), Biman has studied how this uncertainty translates into the resulting fragmentation, with SPH simulation. The results show that the fragmentation process does not depend strongly on this 3-body reaction. This work has been published in the MNRAS.

Working with Kartick Sarkar (JAP student, RRI), Prateek Sharma (IISc, Bangalore) and Yuri Shchekinov (Southern Federal University, Russia) Biman has studied the interaction of supernovae driven outflows from Milky Way type galaxies with the hot halo gas, and how the outflows propagate through this gas. With a Eulerian code PLUTO, they have studied this phenomenon, and connected the observables of outflows (in the inner region, within 5-10 kpc) with the expected mass outflow rate at the virial radius (which cannot be observed, but is needed for cosmological studies). This has also been published in MNRAS.

Massive galaxies contain a large amount of hot gas in their halos, and recent X-ray observations have been able to detect this gas in some cases. Biman along with Priyanka Singh (PhD student, RRI), Subhabrata Majumdar (TIFR, Mumbai) and Joseph Silk (Oxford, UK), have considered the inevitable SZ distortion of the cosmic microwave background radiation due to this gas in galactic halos. This process has not been considered previously, but with the advent of new facilities such as South Pole Telescope, it may become possible to detect this effect. They have calculated the anisotropy power spectrum due to thermal and kinetic SZ effect and discussed its detect ability for various instruments. The results have been reported in the MNRAS.

In collaboration with Eugene Vasiliev (Oxford, UK) and Yuri Shchekinov, Biman has carried out hydrodynamical stimulations to confirm a previous analytical result on the effect of multiple supernovae. Interestingly, the effect of merging of multiple supernovae has never been considered in the literature. In these 2-d and 3-d simulations, they have considered the effect of merging, collisions of multiple supernovae, either exploding at a single epoch, or staggered in time, and found the conditions under which they can give rise to galactic outflows. They have also come up with various observational diagnostics, such as the distribution of radio of OVII / OVIII in starbursts to determine these conditions. This work has led to a publication in MNRAS.

Considering the escape of ionizing photons from disk galaxies and the role of super bubbles around OB associations in this process, since O stars are the main sources of ionizing photons, Biman along with Arpita Roy (JAP student, RRI) and Prateek Sharma (IISc, Bangalore) have carried out extensive simulations. The simulation results show that the escape fraction depends on the fundamental disk parameters such as the gas density and scale height. It has been found that all realistic disk galaxies are likely to have an escape fraction of order ~5-10%, consistent with the requirements from local UV background radiation and re-ionization of the universe. This work has been reported in a paper published by MNRAS.

Biswajit Paul's areas of current research interest include X-ray binaries and transients. His astronomy research in the year gone by has been in the investigation of various aspects of compact X-ray sources and he has made significant contributions to several studies of X-ray binaries.

Aru Beri (IIT-Ropar), Biswajit Paul, Mauro Orlandini (INAF/IASF Bologna, Italy) and Chandreyee Maitra (Service

dAstrophysique, CEA Saclay, France) have carried out a study of temperature evolution during thermonuclear X-ray bursts in LMXBs using broad band data from two instruments onboard Bep-poSAX, the MECS and the PDS. However, instead of applying the standard technique of time resolved spectroscopy, they have determined the temperature in small time intervals using the ratio of count rates in the two instruments assuming blackbody nature of the burst emission and different interstellar absorption for different sources. Data from a total of twelve observations of six sources were analysed during which 22 bursts were detected. In different broadband spectral states of the sources they have obtained temperatures as high as 3.0 keV, even when there is no evidence of photospheric radius expansion.

Nazma Islam (PhD student, RRI), Chandreyee Maitra (Service dAstrophysique, CEA Saclay, France), Pragati Pradhan (North Bengal University) and Paul have also carried out a Suzaku study of a highly absorbed HMXB IGR J16393-4643. The pulsar IGR J16393-4643 belongs to a class of highly absorbed supergiant High Mass X-ray Binaries (HMXBs), characterized by a very high column density of absorbing matter. The group has carried out a simultaneous broadband pulsation and spectrum analysis from a Suzaku observation of this source. The orbital intensity profile created with the Swift Burst Alert Telescope (Swift-BAT) light curve shows an indication of IGR J16393-4643 being an eclipsing system with a short eclipse semi- angle. For different types of the companion star, a supergiant or a main-sequence B-star, this implies different inclination of the orbital plane. Pulse profiles created for different energy bands have complex morphology, which shows some energy dependence and increases in pulse fraction with energy. They have also investigated broadband spectral characteristics, phase-averaged spectra and resolving the pulse phase into peak and trough phases. The phase-averaged spectrum has a very high column density and is described by a power law with a high-energy cut-off above 20 keV. They have found a change in the spectral index in the peak and trough phases, implying an underlying change in the source spectrum.

During the past year, with Nazma Islam (PhD student, RRI), Paul has investigated the orbital evolution and apsidal advance of an eclipsing HMXB 4U 1700-37. Unlike most other HMXBs, 4U 1700-37 is not a pulsar, which makes it difficult to study its orbital evolution, even though a massive companion star and a small orbital period suggests strong orbital decay and significant apsidal advance in 4U 1700-37. Paul and Islam have combined new data obtained using several all sky X-ray monitors (RXTE-ASM, Swift-BAT, MAXI) and RXTE-PCA with all the published mid-eclipse time measurement of this binary to estimate its orbital decay rate. The combined mid-eclipse time measurements spanning about 40 years indicates an orbital decay rate that is smaller by factor of a few compared to its earlier measurement. They infer this to be due to an underestimation of systematic error introduced by X-ray flares in the light curves in the data obtained with pointed instruments like those onboard EXOSAT and RXTE-PCA. Along with the mid-eclipse time measurements, they have also used the eclipse duration measurements to investigate the apsidal advance rate of this system.

Pragati Pradhan (North Bengal University), Enrico Bozzo (ISDC, University of Geneva, Switzerland), Tomaso Belloni (INAF-Osservatorio Astronomico di Brera, Italy), B. C. Paul (NBU)], and Paul have carried out a study of the pulsation and spectral characteristics of 4U 0114+65during the eclipse/partial eclipse. The timing and spectral characterisation of the HMXB pulsar 4U 0114+65 using a Suzaku observation during the orbital phase 0.0-0.1, covering a part of the

eclipse and the egress have been analysed in this work. A time resolved analysis of the data revealed only modest changes in the absorption column density towards the source during the observation. An iron Kα line with an unexpectedly small equivalent width of ~30 eV was observed during the eclipse. The usual equivalent width of similar features in eclipsed HMXBs ranges from 400 eV to 1 keV. In this Suzaku observation of 4U 0114+65, the source count rate during the eclipse and outside the eclipse varied by a factor of only 2-4, at odds with other eclipsing HMXBs where the intensity is observed to change up to 2 orders of magnitude or more. The orbital intensity profile of 4U 0114+65 exhibited an eclipse-like shape in low energies (RXTE - ASM) but a more gradual variation in hard X-rays (Swift -BAT). This is different from eclipse ingress/egress of other HMXBs, which show sharp eclipses in hard X-rays and a more gradual variation in soft X-rays owing to dips, absorption in the stellar wind etc. Both the XIS and PIN data showed clear pulsations during the eclipse. This result is also confirmed by exploiting all the publicly available data from the IBIS/ISGRI and JEM-X instruments on-board INTEGRAL. All these observations indicate that the drop in X-ray luminosity of 4U 0114+65 may not be due to a total eclipse.

Gayathri Raman (PhD student, RRI), Biswajit Paul, Dipankar Bhattacharya (IUCAA) and Vijay Mohan (IUCAA) have investigated the optical reprocessing of X-rays in the LMXB pulsar 4U1626-67 in its current spin-up phase using observations with the Southern African Large Telescope (SALT), near simultaneous observation with Swift-XRT, and non-simultaneous observation with RXTE-PCA. Using fast photometric observations with SALT, they have detected some interesting reprocessing signatures. The absence of optical Quasi Periodic Oscillations (QPOs) in the power spectrum from both the night's data was an expected outcome, characteristic of the spin-up phase of the source, as no corresponding X-ray QPO is seen during this phase. In the light curve obtained on one night, they detected a coherent pulsation at the known spin period. A previously known, slightly downshifted side-band feature is also detected. The light curve of another night displayed short time-scale variability in the form of flares on time scales of a few minutes. The folded pulse profiles resulting from the data of this night showed an interesting trend of the pulse peak drifting with time. The drift of the pulse phase in short time scale could be due to i) short time scale changes in the reprocessing agent, like orbital motion of an accretion disk warp around the neutron star or ii) intrinsic pulse phase changes in the X-rays. They have also examined some X-ray light curves, obtained with RXTE-PCA during 2008-2010 for pulse shape changes in short time scales during the X-ray flares.

Nafisa Aftab (PhD student, RRI), Nazma Islam (PhD student, RRI) and Biswajit Paul have investigated the timing and spectral characteristics of an HMXB pulsar IGR18027-2016 by carrying out a comprehensive analysis of a large number of observations with the Swift-XRT. The long term light curve of this source shows a smooth orbital intensity modulation with a sharp eclipse. However, the out of eclipse observations with Swift-XRT shows strong variations in intensity and pulsation characteristics. In some orbital phases they have detected large difference in flux in multiple observations and also large difference in pulse fraction and pulse profile. Though most of the Swift-XRT observations are short and have limited statistical quality, they carried out spectral measurements to further investigate if the variation in intensity is due to transient absorption by clumpy stellar wind, as is seen in some other HMXBs.

Paul's research activities during the previous year also include extensive developmental work in a number of key projects such as the X-ray Polarimeter, the

the ASTROSAT-LAXPC and a newly proposed X-ray pulsar based interplanetary navigation system. Details on these are as follows –

X-rayPolarimeter:A Thomson X-raypolarimeteroperating in the energy band of 5-30 keV is under development for a small astronomy satellite mission. Anisotropy in the Thomson scattering of polarised X-rays is used to measure the degree and angle of linear polarisation of cosmic X-rays. It is expected that important breakthroughs will be made in some key scientific issues using X-ray polarisation measurements. This Polarimeter is one of the leading contenders for a small satellite astronomy mission of ISRO, and is also among the leading X-ray polarimeter experiments that could be launched in near future. During the period of this report members of the X-ray astronomy laboratory have carried out the following developmental work at RRI.

(i) Calibration of the collimator: The collimator of the polarimeter experiment has a special design with tapered hexagonal holes that gives a flat top response to mitigate any effect of small pointing offset of the satellite. The FOV and angular response of a laboratory unit has been measured and a fixture for calibration of the flight unit has been designed. Fabrication of the fixture is in progress.

(ii) Space qualified electronics: Space qualified cards have been fabricated, populated and tested for the front-end electronics of the X-ray polarimeter.

(iii) Space qualification tests (mechanical): Paul and his group plan to carry out space qualification (mechanical) tests of one of the detectors with its front end electronics. A fixture for the same has been designed and fabricated.

(iv) Processing electronics: PCB layouts have been made for the digital and analogue parts of the processing electronics cards; same have been fabricated and populated. Integrated tests are in progress.

(v) Housekeeping electronics: A laboratory unit of the housekeeping electronics has been designed, made and tested. It keeps records of various housekeeping parameters of the X-ray detectors and the electronics. It has a flexible design to cope with different data rate that may be available from the satellite bus management unit.

(vi) Study of the X-ray polarimeter mission as a small satellite of ISRO has been completed keeping in mind the special requirements for the spacecraft like a stable spin and long three axes stabilised pointing towards different X-ray sources and power generation on a spinning satellite. The configuration of the satellite has been worked out to meet these requirements. These have been done in collaboration with the ISRO Satellite Centre (ISAC). Sample observation plan with the mission has also been worked out for an initial period.

(vii) Development of a photo-electron polarimeter: Paul and his group have been trying to develop a new technique for X-ray polarisation measurement using charge division of a photoelectron track in neighbouring narrowly spaced anode wires in a proportional counter detector. Charge division has been achieved in the energy range of 6-22 keV and they have migrated from kel-f based wireframe to a more flexible PCB based wireframe. Further work is ongoing.

P.V.Rishin, M.R.Golapakrishna, and many members of RAL and MES, RRI have made major contributions to all the development work described above. Varun, (PhD student, RRI) has taken part in the collimator calibration work and development of the photoelectron polarimeter.

Based on the development that has been achieved in this project, its research potential, and successful mission study, the Advisory Committee for Space (ADCOS) of ISRO is scheduled to review it to recommend it for a small satellite mission of ISRO.

ASTROSAT-LAXPC:Paul is currently working with two teams at ISAC, Bangalore and SAC, Ahmedabad towards the development of the ASTROSAT-LAXPC data reduction software. Development and testing of the Level-2 data reduction software and standard processing pipeline for LAXPC has nearly been completed. He has also studied the ground calibration data of the three LAXPC detectors, especially their timing characteristics. Paul serves as LAXPC representative in the ASTROSAT Ground Segment Committee that will take care of the ASTROSAT activities other than the hardware development. He has been a member of the ASTROSAT Science Working Group identifying the baseline science to be carried out with this mission in its early days after launch. Among the various baseline science topics, he is also the coordinator of the group on 'Neutron Star X-ray Binaries'. Among the work that Paul has done independently on this project is the development of data reduction tools and analysis of the LAXPC timing and spectral calibration data, results from which have been very useful LAXPC calibration.

X-ray pulsar based interplanetary navigation system: Paul has carried out some preliminary investigation for development of an X-ray pulsar based interplanetary navigation system. He has studied the stability of the pulse profiles of two sources that have been observed most extensively with the RXTE observatory. Simulations have been carried out to estimate the payload characteristics to obtain useful navigation information. The advantage of such an instrument over the currently used techniques is its position independence and autonomous operation. Some preliminary discussions have already been held with ISRO for a future satellite project.

Mayuri S. has pursued research predominantly in the following two areas during the previous year –

i) Simulation and feasibility studies with an aim to experimentally detect spectral signatures from the Epoch of Recombination and
ii) Application of Maximally Smooth fitting algorithm for foreground modelling towards the recovery of the 21-cm global Epoch of Reionization signal from synthetic sky spectrum.

Researchto study the feasibility of experimentally detecting spectral signatures of the Epoch of Cosmological Recombination was undertaken by Mayuri in collaboration with Ravi Subrahmanyan (RRI), N Udaya Shankar (RRI) and Jens Chluba (Johns Hopkins University / IoA Cambridge). The Cosmic Microwave Background, the relic thermal radiation that fills the Universe, is thought to be the earliest light in the Universe, tracing its origins back to the Big Bang in accordance with the Standard Cosmological Model. The Epoch of Recombination refers to that period in cosmological evolution when the hot plasma content of the early Universe gradually transitioned to the atomic state as the Universe expanded and cooled. Understood to have occurred close to redshift $z \sim 1100$ for hydrogen, $z \sim 2500$ for HeII $\rightarrow$HeI and $z \sim 6000$ for HeIII $\rightarrow$ HeII, the recombination of Hydrogen and Helium is via

capture of free electrons by the nuclei. The electrons trickle down the bound quantum states of the atom proceeding over multiple quasi-stationary states. As the captured electrons in the atoms make bound-bound transitions, the atoms exchange energy with the radiation content of the Universe in the recombination-line transition frequencies. The atoms also undergo multiple dissociations and recaptures until finally the atom arrives at the ground state from the first excited state via either the 2s two photon decay or because of emission of Lyman-alpha photons along with their removal from the background radiation via Hubble expansion. All of the bound-bound transitions result in spectral features in the spectrum of the relict radiation and the redshifts are observable at cm and mm wavelengths today. All physical processes that occurred during the major epochs of cosmological evolution leave 'imprints' in the Cosmic Background Radiation and understanding these imprints hold the key to understanding the early evolution of the Universe.

Mayuri and her collaborators have developed a pipeline to simulate the output of a correlator system recording sky noise temperature to obtain all sky spectra. Inputs to the simulation include parameters such as the observing location, integration time and number of spectra to be recorded, as recorded by an ideal frequency independent antenna. With all sky images available from surveys at 408 MHz, 1420 MHz and 23 GHz, they have developed a code to interpolate between any range of frequencies bound by the limits from the aforementioned maps, using a straight line interpolation in log-log space, to obtain all sky images of the sky, taking care of smoothing - having reduced the three input maps to the same resolution and temperature units. They have taken care of CMB dipole subtraction where necessary and also conversion to uniform HEALPix coordinate systems. Effects of atmospheric refraction and precession are corrected for as well. To the spectra thus generated they have added contributions from Hydrogen recombination as well as HeII $\rightarrow$ HeI and HeIII $\rightarrow$ HeII at corresponding channel frequencies, from data provided by Jens Chluba, Johns Hopkins University, and also thermal noise to the generated spectra. They have estimated the signal to noise ratio to study the feasibility of detection of the recombination lines including various contributions to noise such as CMB, galactic and extragalactic background, atmospheric effects and IR dust extinction apart from the receiver noise. Having identified the most suitable window for an experimental detection they computed the required integration time to achieve a signal to noise ratio of unity and find the number to be acceptable. They have arrived at a method using '***Maximally Smooth***' functions to carefully fit the foreground with the CMB being modelled as a Planck function so that the desired signal can be extracted without being fitted out by the fitting function. This has been a challenging problem in various other problems in astronomy, which involve recovering a weak broad spectral feature from a sky spectrum, which is several order of magnitudes larger than the signal of interest. From statistical tests including MCMC and Bayes Factor analysis they estimate that a detection of the predicted distortions is possible with 90% confidence by observing for 255 days with an array of 128 radiometers using cryogenically cooled state-of-the-art receivers. The results of the feasibility study for a ground based experimental detection of these cosmological recombination signals have been accepted for publication in the Astrophysical Journal.

Working again with Ravi Subrahmanyan and N Udaya Shankar as well as Jens Chluba (Johns Hopkins University / IoA Cambridge), Mayuri has extended the application of the aforementioned '***Maximally Smooth***' functions to distinguish between

the complex foregrounds and the redshifted global 21-cm 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 for accurate modeling. 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. Preliminary results from this group indicate 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 with increasing the order of these smooth functions to any arbitrarily high value. The group is currently running additional tests to confirm these results.

Lakshmi Saripalli's current research interests lie primarily in investigating radio galaxy morphologies, giant radio galaxies and galaxy environments.

A major research project carried out and completed in the year 2014-2015 has been regarding giant radio galaxies (GRGs) and their quite unique relationship with their environments (on both local and large scales). This work is part of the PhD thesis of Jurek Malarecki (University of Western Australia) for whom Lakshmi is one of the supervisors. The work on GRGs and their environments is towards the larger goal of using GRGs to reveal the nature of the elusive warm-hot intergalactic medium (WHIM) in their vicinity.

A sample of 19 GRGs was used in the study of galaxy environments surrounding them. The study was carried out over 2-degree regions around each GRG host galaxy. Optical spectroscopy data was obtained with the Anglo-Australian Telescope for 24726 objects surrounding the sample host galaxies of the 19 GRGs to trace the large-scale galaxy structure in which they were embedded. The GRGs were selected to have redshifts in the range 0.05-0.15. Their projected linear sizes range from 0.8 to 3.2 Mpc. Redshifts could be measured for 9076 galaxies. Using 2.1 GHz radio imaging data obtained earlier by the group for each GRG in conjunction with the surrounding galaxy redshifts, Lakshmi and her collaborators, Jurek Malarecki (UWA, Australia), Ravi Subrahmanyan (RRI, India), Heath Jones (Monash University, Australia), Lister Staveley-Smith (ICRAR, UWA, Australia) have traced large-scale structure in the vicinity of the GRGs. The comprehensive study has allowed a characterization of the environments in which radio galaxies grow to giant sizes and hence the causes for their giant sizes.

They have found that the mean galaxy number over density in volumes of ~700 Mpc^3 near the GRG host galaxies is ~ 70 indicating an over dense but non-virialized environment. Using a Fourier component analysis to quantify the anisotropy in the surrounding galaxy distribution they have found that there is a clear influence of the environment on the GRGs with lobes appearing to be deflected away from over densities in the surrounding medium. Furthermore, the GRG lobes tend to lie normal to the plane defined by the galaxy neighbourhood close to the host indicating the tendency for lobes to grow to giant sizes in directions that avoid dense regions on both small and large scales.

Saripalli's second major theme of research in the past year has been the characterization of morphologies of radio galaxies in a unique sample of 52 radio galaxies selected for their *low axial ratios*. This was done based on radio imaging of available (archival VLA) higher resolution continuum data of the sample. Based on the image analysis they have recognized three main categories of 'distortions' to radio galaxy

morphologies that result in their having low axial ratios: off-axis emission originating from the inner ends of lobes (closer to the host galaxy), off-axis emission originating from the outer ends of lobes (near the hotspots or where the jets terminate) and those where there is a broad swathe of radio emission across the source centered on the host galaxy. Each of these three distortion types is identified with a separate physical and hence occurrence rates for them could be derived. The work has identified radio galaxies (having off-axis emission originating at the outer-ends of lobes), which exhibit clear signs of drifts in black hole axis. The work has also led to identification of 'genuine' X-shaped structures in radio galaxies which otherwise previously have been confused with inner-deviation radio galaxies. These source morphologies are believed to be generated by binary-black hole mergers and hence with the occurrence rate for X-shaped radio galaxies well constrained in this work, they have been able to derive an improved limit to the gravitational wave signal resulting from such mergers. They have derived a value that is nearly 6 times smaller than previously estimated. Saripalli's collaborators in this project were David Roberts (Brandeis University, USA), Ravi Subrahmanyan (RRI, India), Jake Cohen (Brandeis University, USA) and Jing Liu (Brandeis University, USA).

Shiv Sethi is primarily interested in cosmology, epoch of reionization and cosmological implications of primordial magnetic fields.

The detection of EoR in the redshifted HI signal remains a challenging task. Sethi has investigated in detail the efficacy of drift scans to detect this signal using MWA. An advantage of such a strategy is that the system parameters—primary beam, bandpass, etc.– remain fixed during a drift scan. He shows that the visibilities measured at two different times could be strongly correlated depending on the region of sky being observed. In particular, it has been shown that for equatorial scans, the visibilities could be correlated for up to an hour for MWA but it will be shorter (up to 20 minutes for MWA) for other (e.g. zenith scan for the location of MWA) scan depending on the baseline distribution of the radio interferometer. The results show that the sensitivity achieved in such a procedure is comparable to the sensitivity in the usual tracking mode (See Fig. 1). This work was done in collaboration with Sourabh Paul (PhD student, RRI) and the RRI and international MWA EoR team.

Once again in collaboration with Sourabh Paul and the international MWA EoR team, Shiv has analysed MWA tracking and drift scan data and also done simulations to understand the results. They have recently completed the analysis of 8 hours of 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.

Recent cosmological data can throw light on the formation epoch of cold dark matter in the universe. Shiv and Abir Sarkar (PhD student, RRI) and Subinoy Das (IIA) have compared the predictions of many theoretically-motivated Late Forming Dark Matter (LFDM) models with the galaxy clustering and Lyman-α data and show that the dark matter in the universe should have formed before a redshift $z > 10^6$ (See Fig. 2)

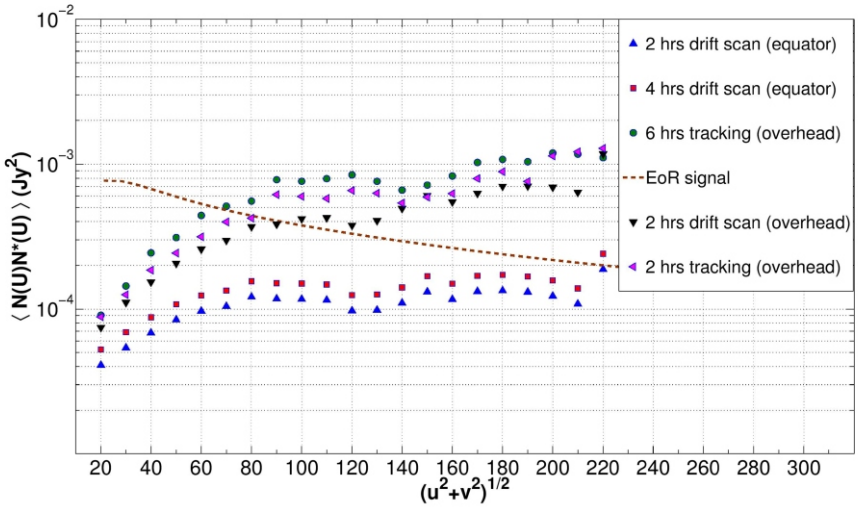


Fig.1: Error on visibility-visibility correlation as a function of baseline length: blue (triangle), red (square) refer to 2 hours equatorial drift scan, respectively. Black (inverted triangle) points refer to 2 hours zenith drift scan at the location of MWA. The green (circle) and pink (rotated triangle) points show the expected error for 2 and 6 hour tracking runs for ± 1 and ± 3 hours continuous overhead tracking at MWA location. In all the cases the total integration is 900 hours. The dashed brown line shows the EoR signal. [Image Credit: Paul, S. Sethi, S. et al. (2014): Study of redshifted HI from the epoch of reionization era with drift scan, ApJ, 793, 28]

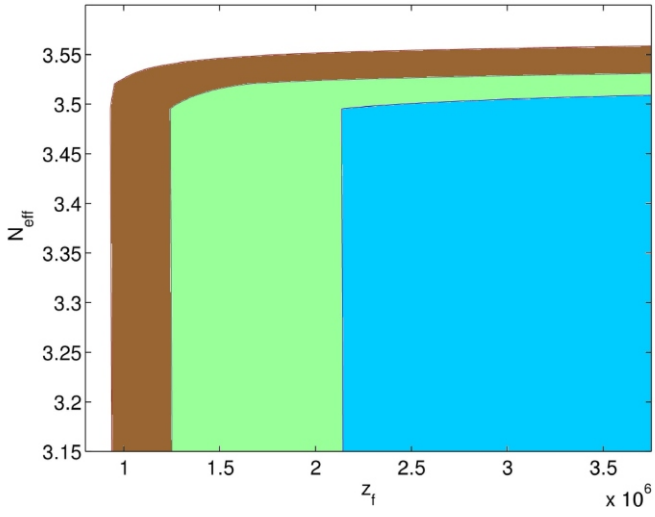


Fig.2: The allowed region in the plane of the formation redshift of dark matter z_{eff} is shown for the Lyman- α data. The blue, green and the brown regions indicate the 68%, 95.4% and 99.73% confidence levels, respectively. [Image Credit: Sarkar, A. Das, S., Sethi, S. (2015): How late can the dark matter form in our universe, JCAP, 03, 004]

Working with Kanhaiya Pandey, Tirthankar Roy Choudhury (both NCRA), and Andrea Ferrara (SISSA, Italy), Shiv has used data in the redshift range 6 < z < 10, to attempt to constrain primordial magnetic fields are possible sources of density perturbation in the early universe. They have showed that the inclusion of primordial magnetic fields improved the agreement between theoretical models and observational data. It has been shown that magnetic fields as small as 0.1 nG can have significant impact on reionization history, which is the smallest bound hitherto obtained (See Fig. 3).

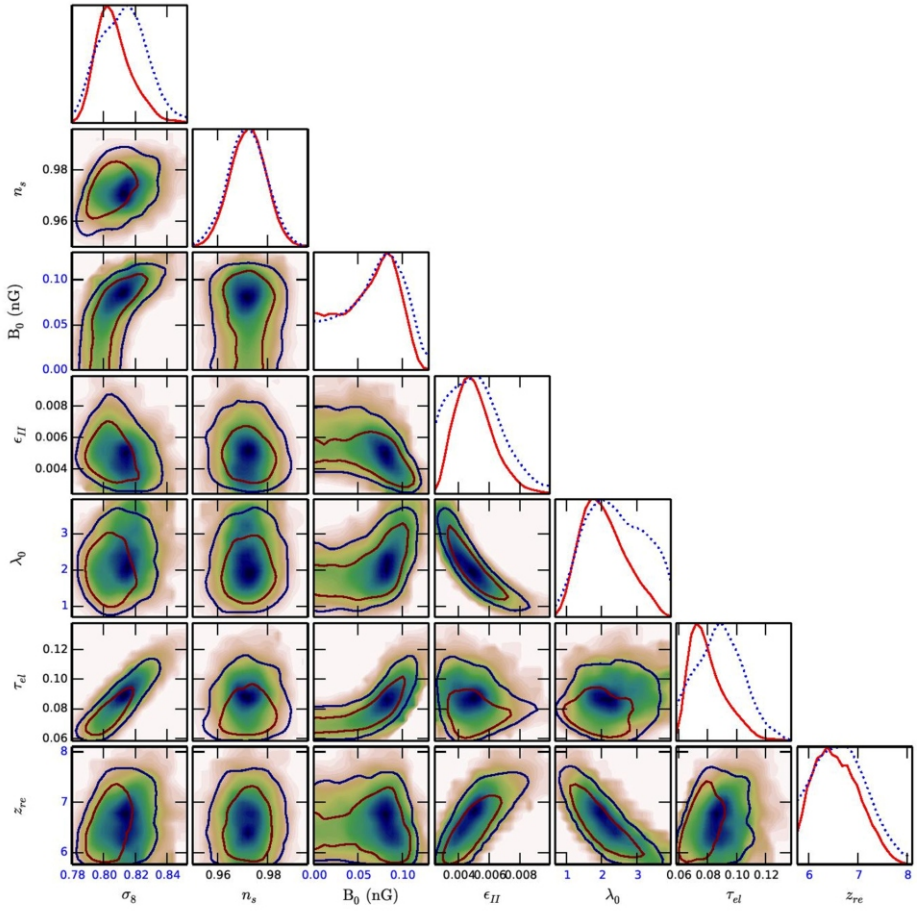


Fig.3: Confidence intervals for the magnetic field power spectrum n = -2.9 are shown for the five parameters considered in the reionization model.

Using SARAS, a correlation spectrometer developed in-house at RRI, radio background at low frequency (110-175 MHz) was measured with unprecedented precision. This measurement was used improve the calibration of the existing all-sky map at 150 MHz (See Fig. 4). These measurements also indicate that the spectral index of galactic emission flattens toward the Galactic budge region. This work was done in collaboration with Nipanjana Patra (PhD student, RRI), Ravi Subrahmanyan (RRI), Uday Shankar (RRI) and A. Raghunathan (RAL, RRI).

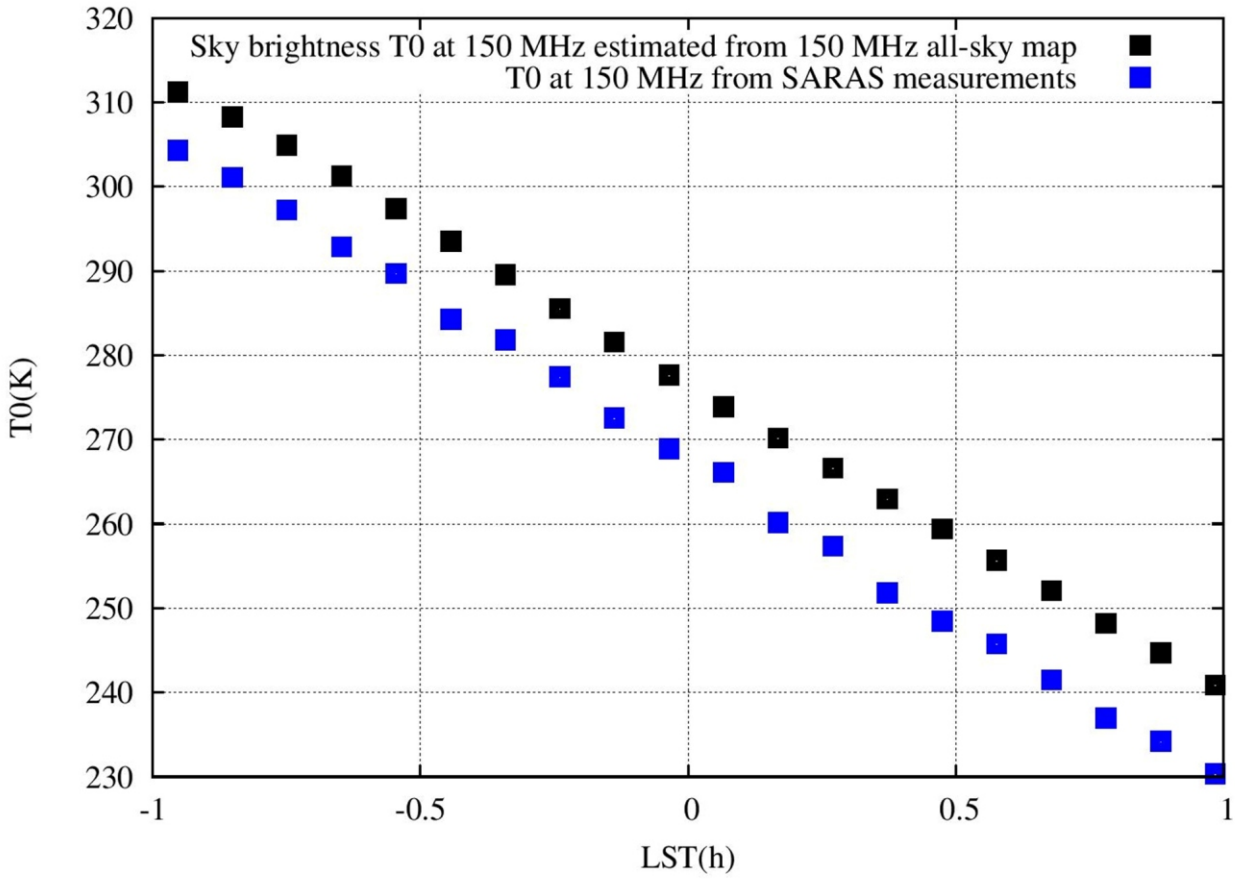


Fig.4: A comparison between SARAS measurements and the existing all-sky 150 MHz map (smoothed to the angular resolution of SARAS). [Image Credit: Patra, N. Subrahmanyan, R., Sethi, S. Udaya Shankar, N. Raghunathan, A. (2015): Saras Measurement of the Radio Background At Long Wavelengths, ApJ, 801, 138]

N. Udaya Shankar's areas of current research interests mainly focus on building self-calibratable systems for the detection of signals from the Epochs Of Reionisation (EoR), and Recombination.

In the period between 2014-2015, in collaboration with Saurabh Singh & Nipanjana Patra (Ph.D. students, RRI), A. Raghunathan (RAL, RRI) and Ravi Subrahmanyan (RRI), Udaya Shankar worked on experiments to detect the all-sky signal from the Epoch of Reionization (EoR). Detection of signals from neutral hydrogen atom at the time the first luminous objects in the universe were born is challenging. Detection helps the astronomer 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. Last year there was considerable progress towards the goal of building a system capable of a useful measurement of spectral signatures of the EoR in the cosmic radio background.

Deployment of prototype systems in the field and analysis of the data yielded an accurate measurement of the absolute brightness and spectral index of the radio background between 110 and 175MHz. They have been able to measure the absolute sky brightness to 1.2% accuracy, only limited by the systematic errors. The group used the wide-angle measurement derived by the SARAS,

a correlation spectrometer purpose designed for precision measurements of the cosmic radio background to provide an improved absolute calibration for the 150MHz all-sky map of Landecker and Wielebinski: they showed that subtracting an offset of 21.4K and scaling the resulting image by a factor of 1.05 will reduce the overall offset error to 8 K (from 50K) and scale error to 0.8% (from 5%).

The finding is also beneficial to modelling the global foreground sky, an essential step to detect the global EoR signal. The SARAS measurement of the temperature spectral index indicates that the spectral index of the radio sky is steeper off the Galactic center region and perhaps also off the Galactic plane. Their observation is consistent with what is expected in a simple diffusion model where high energy cosmic ray electrons originate in star-forming activity and consequent supernovae in the Galactic disk and diffuse into the Galactic halo, with spectral steepening owing to synchrotron losses and inverse Compton scattering. The results of this observation have been reported in the *"The Astrophysical Journal"*.

The data analysis has also indicated that the observations are limited in sensitivity by the systematics of the receiver and the man made Radio Frequency Interference environment in GBD observatory. So a four-pronged approach has been adopted:

1. Redesigning the analog receiver to incorporate an in situ measurement of the return loss of the antenna.
2. Redesigning the frequency independent antenna of SARAS focusing on a smoothly varying return loss for the antenna so that reflections does not result in spectral structures which are similar to the EoR signal.
3. Increasing the operating bandwidth to cover the frequency range 40-200 MHz in tune with the present understanding of the Dark ages and onset & end of the reionization epochs.
4. Designing a spectrometer to accommodate the wide bandwidth of the receiver also aiming for a high dynamic range to minimize loss of channels due to strong RFI.

Redesigning the analog receiver is an ongoing exercise. As a first step they have included an additional noise source to the SARAS configuration to carry out in situ measurements of the antenna return loss. When it comes to the antenna used they have tried out many different shapes guided by the following principles.

I) They ideally desire a frequency independent antenna and short dipole (or a monopole) satisfies their requirement. So they kept the size of the antenna at a maximum of half a wavelength at the highest frequency of operation.
ii) Then they desire an antenna with a single main lobe with null towards the horizon to minimize the radio frequency interference, ground spillover to minimize system noise and maximize antenna gain, minimize ohmic loss to reduce the additive terms appearing at the output of the receiver.

These requirements have driven them towards monopole antennas. While most of the antenna designers look for high return loss, they have not imposed a strict requirement on this parameter in their design, since it is the antenna temperature that dominates the receiver noise throughout the frequency band of interest. In this connection they are currently experimenting with monopole discone antennas and a modified version of volcano smoke antennas.

During the last academic year, Udaya Shankar along with Mayuri S.,

Ravi Subrahmanyan and Jens Chluba (Johns Hopkins University) has also been engaged in designing an experiment to detect the all-sky signal from the Epoch of Recombination in the radio window. In 2012-13, as a part of the flagship program of RRI, the group had proposed to build an Array of Precision Spectrometers (APSERa) - to detect recombination lines from the Epoch of Cosmological Recombination (See www.rri.res.in/DISTORTION for more details).

It is well known that the frequency spectrum of the Cosmic Microwave Background (CMB) is a blackbody spectrum to a precision of 50 parts per million. However there are small temperature fluctuations at the level of one part in 10^5 when observed in different directions in the sky. In addition at higher sensitivity the CMB spectrum is expected to show distortions from the blackbody shape. These distortions contain the signatures of energy-releasing processes in the early universe and their study can open a new window into the physics of the early universe.

At RRI they are focusing on studies and experimental detection of weak spectral distortion of the Cosmic Microwave Background by the photons emitted during the epochs of Hydrogen (500 <z < 2000) and Helium recombination (1600< z <3500 for HeII to HeI and 5000 < z < 8000 for HeIII to HeII). In 2014-15 they carried out a feasibility study for an experimental detection of these recombination lines. Several questions were asked and answered by the study:

(1) What is the most suitable frequency range for a ground-based detection experiment?
– The study showed that an octave band in the 2–6 GHz window is an optimal choice from considerations of maximizing the signal-to-noise ratio and observing with adequate frequency span so as to include sufficient recombination line spectral structure. In this cm-wavelength radio band the predicted signal appears as a broad and weak additive component with variable amplitude of about 8 nK embedded in a sky spectrum that is some eight orders of magnitude brighter.

(2) Is it possible to recover the cosmological recombination lines from the total sky spectrum?
– The study showed that it is indeed possible and they 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 the group has introduced the concept of Maximally Smooth function that is capable of describing the foreground spectrum and distinguishing the signal of interest. They found that these distortions are detectable with a 90% confidence by carrying out 255 days of observations in the centimeter wave region of the sky with a 128-element array of radiometers that use cryogenically cooled state-of-the-art receivers. These findings have been reported in a publication to appear in *"The Astrophysical Journal"*.

Collaborating with Srivani, B.S. Girish (RAL, RRI) and Ravi Subrahmanyan (RRI), Udaya Shankar has also been involved in the designing and commissioning of high speed and high dynamic range spectrometers (pSPEC) for cosmological studies. As a first step in this direction the APSERA team designed a state of the art FPGA based precision digital spectrometer board (pSPEC) capable of digitizing analog signals with bandwidths wider than 1 Ghz. The spectrometer is based on high speed ADCs functioning in the interleaved mode to achieve

the desired bandwidths and Fast Fourier Transform (FFT) preformed using virtex6 FPGAs. While success was first tasted using this system in 2013-14, fine-tuning took place in 2014-15, which resulted in its development as a general-purpose platform for high dynamic range spectrometers for precision cosmology receivers.

In 2014-15, the platform was configured to form the digital back-end receiver for the experiment to detect the HI signal from the EoR. Now the group has a working system capable of digitizing two signals each with a 250 MHz analog bandwidth using 10-bit ADCs, followed by a virtex6 based parallelizable FFT engine capable of providing 8192 spectral channels. This is followed by a cross power spectral estimation for user-defined integration periods and then spectra are streamed out using the gigabit Ethernet interface, integrated on-chip for a period of about 67 msec at about 2 Mbytes per second. Presently the spectrometer is integrated in a mechanical enclosure unit. The system integration and testing along with the analog unit is in progress. Various aspects related to system integrity, stability, quality of the results and software fine-tuning are being addressed.

There has been substantial progress configuring the pSPEC platform for the group's larger experiment to detect signals from the Epoch of Recombination. Two pSPEC units have been reconfigured for use with Virtex®-6 SXT FPGAs, which are optimized for systems requiring ultra-high performance digital signal processing with low-power and a 6.6 Gbps serial connectivity. This chip delivers the highest ratio of DSP and memory resources. With this modification they are pushing the fine-tuning of the pSPEC platform to function as a spectrometer for analog signals with a bandwidth of 2.5 to 3 GHz.

S. Sridhar worked in two areas of Dynamical Astronomy, both of which involve the physics of N-body gravitating systems. The first, Exoplanetary Dynamics, is a few-body (N < ten) problem. The second, Stellar Dynamics around a Massive Black Hole, is a many-body (N > million) problem.

In joint work with Jihad Touma (American University of Beirut, Lebanon), Sridhar proposed a new mechanism that could affect Multiplanet Systems in Binary Stars. Most exoplanetary systems in binary stars are of S-type, and consist of the planets orbiting a primary star, with a binary companion star on a distant orbit. A nearly circular and planar planetary system has a set of normal modes, called the (eccentricity) Laplace - Lagrange secular modes, corresponding to rates at which the long axes of the orbits precesses. It is well known that orbital precession is orders-of-magnitude slower than Kepler orbital times. But it has not been appreciated that the orbital precession periods can be comparable with (or be in resonance with) the period at which a distant binary orbits. Capture of one or more modes into this *Laplace-Lagrange Evection Resonance* (LLER), and subsequent interplay with planetary mean-motion resonances, can lead to dramatic results. These can range from excitation of large planetary eccentricities and mutual inclinations to total disruption, as Touma and Sridhar demonstrate through different kinds of numerical simulations, analytical modelling, and analysis of data from the Open Exoplanet Catalogue. An initially non-resonant planetary system can be brought into resonance by various processes, one of which is planetesimal-driven planetary migration. As it does not require special physical or initial conditions, LLER is a generic process. In addition to altering the architecture of many S-type systems, LLER can also weaken the multi planet occurrence rate in wide binaries and affect planet formation in close binaries.

One of Sridhar's primary research interests is dense clusters of N (> million) stars orbiting massive black holes in the centres of galaxies. Observations of the central regions of our Galaxy and the Andromeda galaxy reveal that nuclear star clusters can have interesting spatial geometries of low spatial symmetry (eccentric, lopsided, warped, thick, triaxial) with associated kinematics (precessing or counter-rotating). Sridhar and Touma (1999) argued that in `Keplerian' star clusters (in which the black hole's gravity dominates the self-gravity of all stars) the orbits of stars are more regular, and this could enable self-consistent secular self-gravitating equilibria of the desired low spatial symmetry. There has since been some progress in our appreciation of these systems. Over the past year Sridhar worked on various problems concerning the structure and dynamics of zero-thickness self-gravitating Keplerian discs, in collaboration with Tarun Deep Saini (IISc, Bangalore), Mamta Gulati (IISER, Mohali), Karamveer Kaur (PhD student, RRI,) and Naveen Jingade (IISc, Bangalore). Secular time evolution is driven by the small self-gravity of the stellar system. But a general theoretical framework is absent, owing to the difficulties in dealing with the long-range and purely attractive nature of the gravitational force. Sridhar and Touma (AUB) have developed a theory of the secular (or long-term) evolution of self-gravitating Keplerian stellar systems. This provides a general framework to describe both the collision less dynamics and non-equilibrium statistical mechanics. They can now describe precisely

(a) Secular collision less equilibria and their dynamical stability and
(b) The slower kinetic evolution, owing to 'resonant relaxation', toward a secular-thermodynamic equilibrium state.

Viral Parekh is interested in galaxy clusters, diffuse radio sources and developed radio data reduction pipeline. In collaboration with K.S. Dwarakanath (RRI), Ruta Kale (NCRA-TIFR), and Lijo George Thomas (PhD student, RRI), Parekh has been working on exploring diffuse radio sources in MWA continuum survey.

Radio observations have shown the existence of diffuse large-scale emission from the intra-cluster medium (ICM), suggesting that non-thermal components, magnetic fields and relativistic particles, are mixed with the hot ICM. The diffuse extended cluster-wide radio sources are currently grouped in two classes: radio halos (RHs) and relics. The RHs are found at the central cluster region, with typical extent ~1 Mpc and steep spectra (alpha = 1-1.8). The relic sources are similar to the halos in their low surface brightness, large size and steep spectrum, but they are typically found in the peripheral regions of the cluster. These sources are important to study distribution of magnetic fields and relativistic particles, dynamical activity of cluster (merger-halo connection), cluster history and evolution, etc. They are important as they provide a way to study large-scale structure formation in the Universe and for comparison with cosmological models. Because of low statistics of these sources, very little is known about origin and evolution of these sources. Measuring the occurrence of RH in clusters and its connection with cluster properties is a challenging task. Current solid statistical information refers essentially to a relatively narrow range of redshift (z=0.2-0.35) and to X-ray luminous (and very massive) clusters. Extending these constraints both in (high) redshift and (low) mass range is vital to understand the origin of cluster-scale radio emission and to test the predictions of theoretical models. The statistical properties of RHs can be used to discriminate among various models for the origin of non-thermal

particles in galaxy clusters.

In this project, the aim is to use MWA-GLEAM (The GaLactic and Extragalactic MWA Survey) data to search for new diffuse radio sources in galaxy clusters. As a starting point, the group is using MCXC (a Meta-Catalogue of X-ray detected Clusters of galaxies) catalogue to locate cluster position and utilise available X-ray information of galaxy clusters such as mass, luminosity, temperature, etc. Then they are comparing flux density of central sources of galaxy clusters at 150 MHz data of MWA with the NVSS (1.4 GHz) or the SUMSS (843 MHz) depending on the availability of data in these later observations. Parekh also uses TGSS (150 MHz) observations for this work. Simultaneously, the X-ray morphology of the corresponding galaxy cluster is being checked using ROSAT, Chandra and XMM- Newton X-ray telescopes. If the central source of galaxy cluster exhibits a steep spectra, and corresponding X-ray data and disturbed morphology both indicate towards the chance of hosting radio halo. Then they work at higher resolutions and use sensitive follow-up observations with GMRT. Currently, they are limited by poor resolution (~ 3 arcmin at 150 MHz) of the MWA data. Current MWA data is not sufficient to study diffuse radio sources.

In Parekh's initial work, they had selected 130 galaxy clusters from the MCXC catalogue based on redshift and luminosity. As stated above, because of poor resolution of current MWA data, from 130 galaxy clusters, they had to further select sample clusters based on a central source that does not have many point sources around it in the corresponding high resolution NVSS image (otherwise in MWA image, these point sources blended with central source). For each of these selected clusters they made a primary beam corrected image of MWA. Then they measured spectral index for this central source of cluster between 150 MHz and 1400 MHz frequency bands. From this ongoing work, they selected ~10 promising candidates (based on steep spectrum source and X-ray morphology) for further studies with GMRT. Recently, they have secured time for low frequency (610 MHz and 235 MHz) GMRT observation for these clusters to search for diffuse radio emission. They are also analysing several other promising clusters using VLA and GMRT archival data.

Finally, Parekh is also engaged in another project with Ruta Kale (NCRA-TIFR) on radio sources in the Massive and Distant Clusters of the Wise survey (MaDCoWs). They have recently got 40 hrs to observe seven distant clusters ($0.7 < z < 1.3$) using GMRT (610 MHz and 1400 MHz). In this project, the primary aim is to detect diffuse radio emission in distant clusters.



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 nano materials, laser cooling and trapping of atoms, molecular spectroscopy, cold collisions, investigations on spin statistics, 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, etc. Currently, quantum logical gates are being designed by tailoring the internal degrees of freedom of quantum optical tools in external potentials.

Current Research Interests

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 involving low-intensity probes for atoms prepared in a superposition state, and Quantum Non-demolition (QND) measurements of quantum superposition states have been designed.

Another line of quantum optics research in LAMP focuses on the creation and manipulation of quantum correlations, and their transfer from photons to material objects. These material objects range from being in a state which is gaseous, with a dilute collection of loosely bound atoms, to solid state objects which have micrometer dimensions like a micro mechanical spring. A comprehensive study of photon-matter interactions within such a dynamic range in sizes and states of matter is carried out to answer how quantum properties are created, stored and retrieved in such diverse systems. This research may also unravel fundamental constraints involved in creating quantum properties in matter with mesocopic dimensions, existing at room temperature.

Just as transfer of quantum correlations from photons to material objects, the LAMP GROUP is also studying transfer of quantum correlations from one frequency to another frequency currently. In particular, it has been observed that Rubidium atoms, with which bichromatic light fields interact to create the Electromagnetically Induced Transparency (EIT) effect, also have a magnetic dipole transition in the microwave regime. Connecting this transition to a microwave field gives rise to a Delta system with many interesting properties such as phase sensitive amplification of external electromagnetic fields applied on the Delta system.

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 and weak value amplifications in atom-photon interactions are being studied both theoretically and experimentally by the group in various systems, for example in the resonance fluorescence spectrum of an atomic system with a V-level structure.

Laser cooling and trapping

Laser cooling and trapping is a fairly novel technique that has gained huge popularity throughout the world of physics since 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. Or 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 using a MOT is that of time-delayed intensity-interferometry of emission from laser-cooled atoms. The significance of this method lies in its ability to determine whether a light source is chaotic (thermal) or coherent or quantum (squeezed) by examining the correlation between the photons emitted by such a source. The LAMP group at RRI has employed this technique to test for the coherent and incoherent dynamics of a large thermal ensemble of atomic emitters by measuring the correlation function of emission from a collection of laser-cooled rubidium atoms in a MOT.

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 are being formulated. Conceptually, this would imply stepping up the scope of the ion-atom physics being accessed by these experiments to the next level i.e. the quantum level.

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, have 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-level, 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.

Electromagnetically induced transparency (EIT)

EIT is a quantum mechanical phenomenon where, under specific conditions, an 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. One such example currently being investigated by the LAMP group is the possibility of non-linear generation of microwaves in a Delta EIT system of Rubidium within a high-finesse microwave cavity.

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 extremely important breakthrough in the design of continuous, flicker-free display device 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 carry a lot of importance in the current theoretical physics scenario where a lot of importance is being given to 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 realizations 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 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.

The Quantum Information and Quantum Computation lab at RRI has started a new experiment involving single photon sources, which will infer expectation values of non-Hermitian operators using the concept

of weak interaction, a possibility already proved analytically by the same lab. A Mach Zehnder interferometer is being set up for this purpose.

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 Graphene, quantum dots (CuS), multiferroic nanoparticles, polymer films, metal oxide nanostructures and semiconductor-metal nano-composites, such as (ZnO:Au).

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 and Zinc)) 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).

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

This year Reji and his team of doctoral and visiting students worked in two major directions, the first of which is the broad research theme of spectroscopic studies of ultrafast laser produced plasmas. They investigated Optical Time of flight dynamics of slow neutrals, fast neutrals and ions present in nanosecond and femtosecond laser produced plasmas (emitted by irradiated Nickel and Zinc targets). The second direction is the study of optical nonlinearity in nanostructured and other materials.

From the plasma time of flight studies it was shown that ions recombine to form neutrals as they move away from the target surface, and measurements of species arrival times experimentally confirmed the earlier hypothesis that fast neutrals are formed by the recombination of fast ions with free electrons. Both neutrals and ions are found to accelerate for a short interval immediately after ablation, which is attributed to internal Coulomb forces creating electrostatic potentials resulting in charged particle acceleration. This process is further enhanced by laser-plasma energy coupling in ns excitation. Plasma plume imaging performed at various ambient pressures indicates adiabatic expansion at lower pressures and plume front deceleration at higher pressures. While at lower pressures the plume front-time (R-t) plot displays a linear expansion, the shock wave model fits to the data at intermediate pressures (5 Torr), and at higher pressures the data fits better to the drag model. In particular, around an intermediate pressure of 10 Torr, the R-t plot is found to fit to the shock wave model at earlier stages of plasma expansion, while it fits to the drag model at the later stages. These investigations provide important information on the acceleration of ions and neutrals in expanding plasma plumes produced by ultrafast laser pulses. Results obtained have been published.

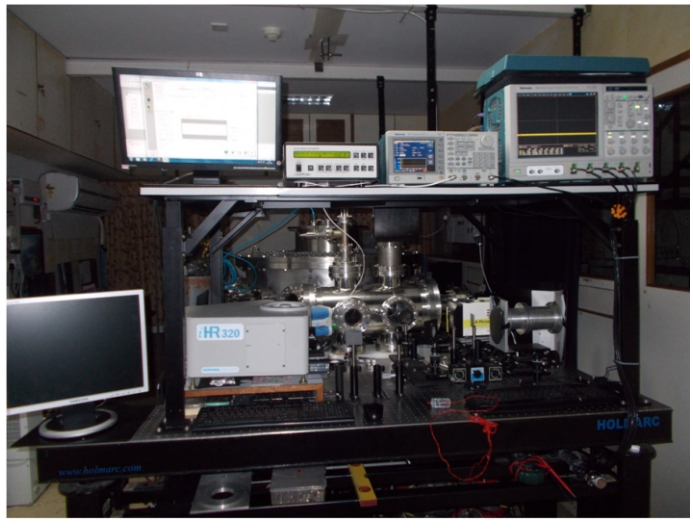


Figure 1: Experimental set up for laser produced plasma generation in the Ultrafast and Nonlinear Optics (UNO) lab. Instruments include ultrafast (femtosecond) and short pulse (nanosecond) lasers, vacuum chamber and pumps, spectrometer with CCD and PMT detectors, ICCD imager, laser energy meters, function generator, and fast oscilloscope.

Ongoing Research

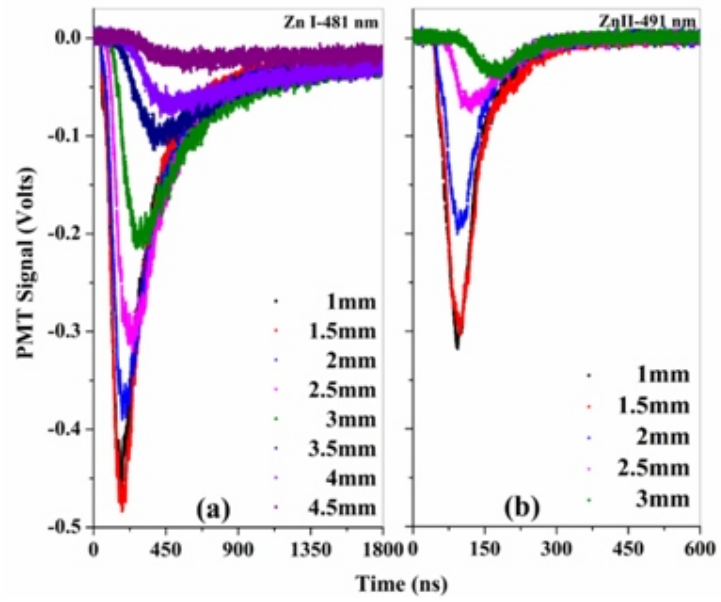


Figure 2: The velocities of the species ejected from the target in a laser ablation process can be determined from optical time of flight measurements. Here, the flight of neutral zinc (Zn I) and singly ionized zinc (Zn II) from a Zn target ablated by 100 fs laser pulses is mapped in time using a monochromator and PMT. Zn I emits at 481 nm and Zn II emits at 491 nm. The background gas pressure is 50 Torr [Image Credit: Smijesh, Rao and Reji Philip, (2015): Dynamics of neutrals and ions in an ultrafast laser produced Zn plasma, Physics of Plasmas 22, 033509].

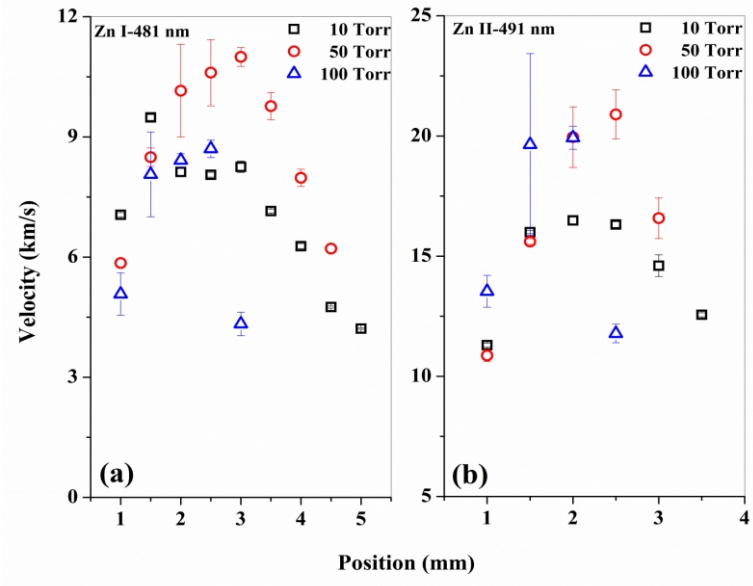


Figure 3: Velocities of peaks corresponding to (a) neutrals and (b) ions, in the Zn plasma plume, plotted against the distance of measurement from the target surface. Error bars are calculated from multiple measurements. Ions are found to accelerate near the target surface. Since some of the accelerating fast ions recombine with the slow electrons in the plume to generate fast neutrals, acceleration of neutrals also can be observed [Image Credit: Smijesh, Rao and Reji Philip (2015):Dynamics of neutrals and ions in an ultrafast laser produced Zn plasma, Physics of Plasmas 22, 033509].

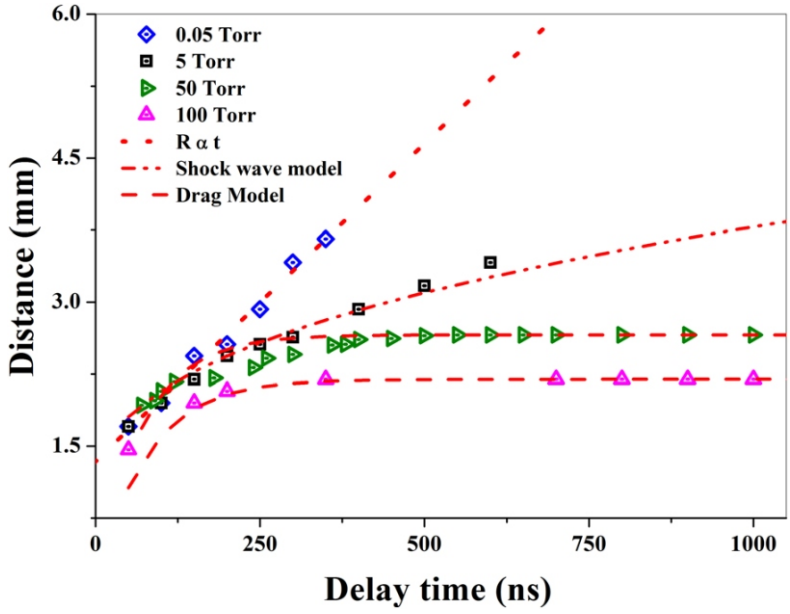


Figure 4: Plume front vs. time (R-t) plots for low and high ambient nitrogen pressures, calculated from ICCD images. Symbols represent data and dashed lines represent plume expansion models. Free expansion model fits at 0.05 Torr, shock wave model fits at 5 Torr, and drag model fits at 50 Torr and 100 Torr. A small deviation from the drag model seen at 50 Torr for ≤ 400 ns may be due to shock wave effects present in the earlier stages of expansion [Image Credit: Smijesh, Rao and Philip, (2015): Dynamics of neutrals and ions in an ultrafast laser produced Zn plasma, Physics of Plasmas 22, 033509].

The occurrence of multi-photon Raman scattering in semiconductor-metal (ZnO:Au) nanocomposites was studied in collaboration with B. Karthikeyan (NIT Trichy). Enhancement of Raman scattering and nonlinear absorption happens in metal-semiconductor nanocomposites due to local field enhancement. Local field enhancement factors were calculated for the investigated ZnO:Au sample. Another study was on the role of surface states and defects in the ultrafast nonlinearity of CuS quantum dots (CuS). In CuS, the smaller crystallite size and quantum dot formation have significant effects on the high-energy excitonic and low-energy plasmonic absorption bands. Effective two-photon absorption coefficients measured using 100 fs laser pulses employing open-aperture Z-scan in the plasmonic region of 800 nm reveal that CuS quantum dots are better ultrafast optical limiters compared to CuS nanoparticles (which are relatively bigger in size).NLO properties of novel blue light emitting truxene discotic liquid crystals (prepared in the lab of Sandeep Kumar, RRI), were studied. Multiferroic nanoparticles, graphene composites, polymer films, and metal oxide nanostructures also were investigated.

In his NLO research Reji usually collaborates with experts who can synthesize novel materials in the laboratory. This year the collaborators were Mark G. Humphrey (Australian National University, Canberra), Tae Joo Park (Hanyang University, South Korea), J. Thomas (University of Central Florida, Orlando, USA) and N.V. Unnikrishnan (M.G. University, Kottayam).

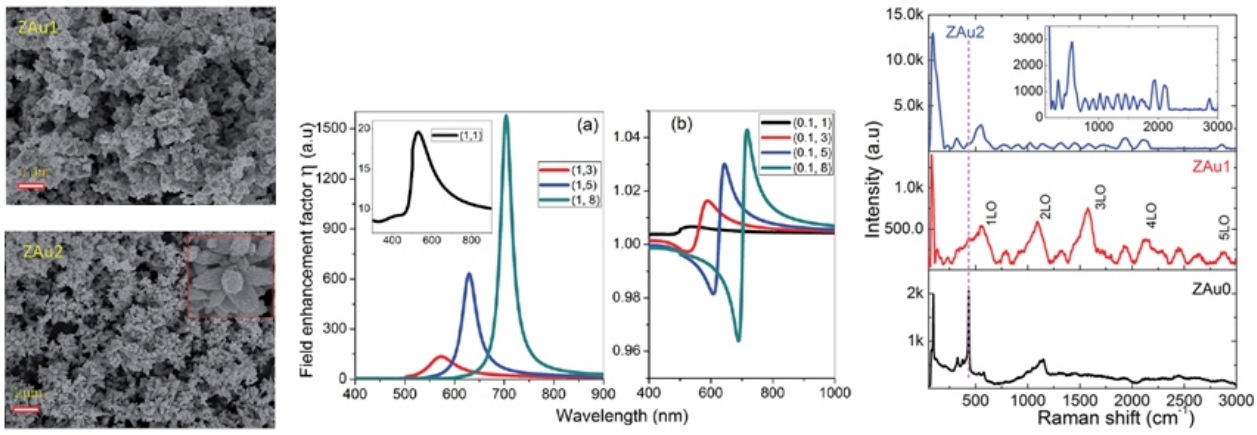


Figure 5: A metal-semiconductor nanocomposite yields enhanced Raman scattering and stronger optical limiting. Here, SEM images show the nanostructure of ZnO:Au nanocomposites (ZAu1, ZAu2). The structure results in local field enhancement when exposed to a laser beam, yielding enhanced Raman scattering [Image Credit: Udayabhaskar, Karthikeyan, Sreekanth and Reji Philip, (2015):Enhanced multi-phonon Raman scattering and nonlinear optical power limiting in ZnO: Au nanostructures,RSC Advances 5, 13590]

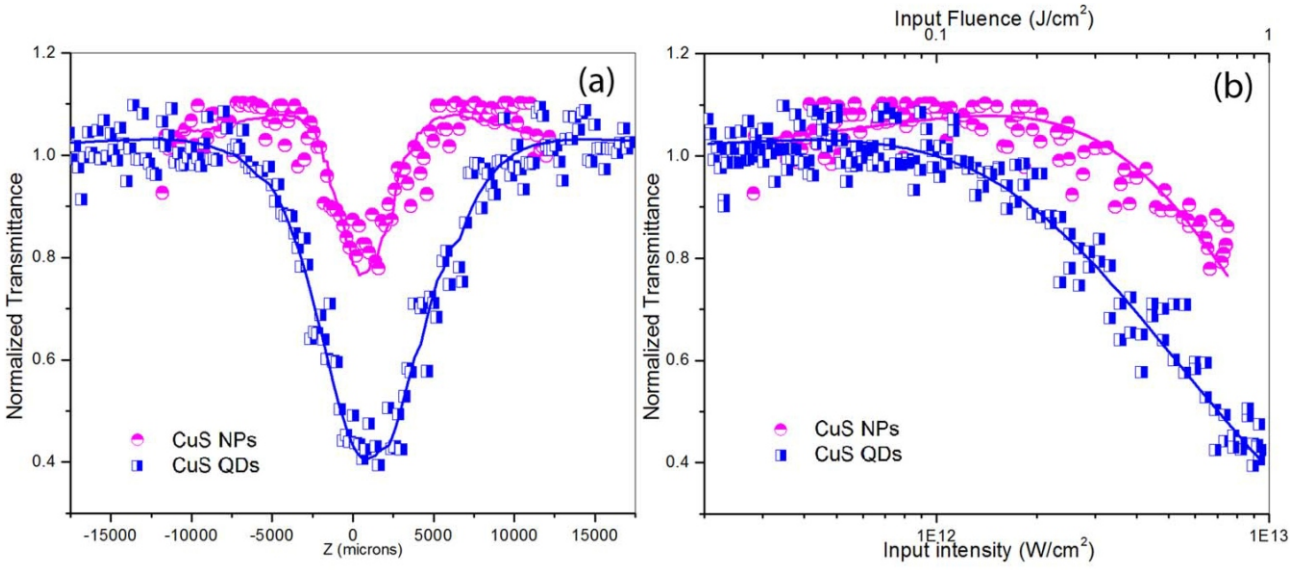


Figure 6: Semiconductor quantum dots and nanoparticles show different NLO behavior. This figure depicts open aperture Z-scan curves measured in CuS QDs (2-4 nm diameter) and NPs (5-11 nm diameter) excited by ultrafast (100 fs) laser pulses at the plasmon resonance wavelength of 800 nm. While QDs exhibit a predominantly optical limiting behavior, NPs exhibit absorption saturation at moderate input intensities followed by limiting at the higher intensities [Image Credit: Mary, Unnikrishnan and Reji Philip, (2014):Role of surface states and defects in the ultrafast nonlinear optical properties of CuS quantum dots,APL Materials 2, 076104].

During the previous year, Reji and his team have used the FESEM a few times, and the Raman spectrometer once. Since Raman is essential for the characterization of carbon allotropes he expects to use the Raman system more frequently in future. The ultrafast and short pulse lasers and associated equipment in his lab, bought through RRI funds, were extensively used as follows:

- Ultrafast laser system (100 fs, Ti:Sapphire) : for
  (i) Spectroscopic studies of ultrafast laser produced plasmas from a solid zinc target, and
  (ii) Ultrafast optical nonlinearities in CuS quantum dots.
- Short pulse (5 ns, Nd:YAG) laser system: Optical nonlinearity in several nanomaterials.

Andal Narayanan's current professional research interests are in quantum optics with atoms and light and quantum measurements in atom-quantum optics.

Her first research theme in the year gone by has been a study of the enhancement and amplification in a Delta atomic system, expanding their earlier research theme based on Electromagnetically Induced Transparency (EIT) effect, to an entirely new area of transfer of quantum correlations from one frequency to another frequency based on EIT effect. This is made possible because, Rubidium atoms with which the bi-chromatic light fields interact to create the EIT effect has a magnetic dipole transition in the microwave regime. Connecting this transition with a microwave field gives rise to a Delta system. This system has many interesting properties. One such is the process of amplification of one or more fields interacting with the Delta system. This amplification process is phase sensitive and will be able to provide phase control of transmission and absorption spanning from microwave to optical frequencies.

Narayanan along with her collaborators Satya Sainadh (Griffith University, Brisbane), Manu Kumar M (Visiting student, RRI), Barry Sanders (IQST, Calgary, Canada) and Asha K (Joint Ph.D student, Kuvempu University) are in the process of experimentally verifying amplification in one or two of the electromagnetic fields interacting with a Delta system. They have also developed a theory incorporating the effect of thermal bath on atom-field interactions in a Delta system.

Closed loop interactions between electromagnetic waves and induced atomic dipoles connecting cyclic transitions give rise to many interesting effects. One such is amplification, which can be seen in either one or two of the three interacting fields. Amplification is defined as a process where the output intensity of a field is greater than its input intensity. In experiments conducted so far enhancement of optical probe field in the presence of coupling and microwave fields is seen, but true amplification of probe field was not seen. To understand the reason behind the absence of amplification at room temperature, Narayanan wanted to develop a system-bath model for the Delta atomic system, interacting with not only the three electromagnetic fields, but also with a thermal bath at 300 K. The expectation was that the bath photons would introduce maximum phase decoherence for transitions in the microwave regime, and that would be the reason behind the absence of amplification in the optical probe field. Using density matrix formalism they have introduced a Markovian interaction with the bath and developed a realistic model of the Delta system interacting with the three EM fields and with the various bath modes. Fig. 1 shows a phase plot with temperature (T) and decay between the ground states (g_c) variables, identifying regimes of enhancement of optical probe field in the presence of the microwave field and regimes

of probe amplification. A shows region of amplification, B shows region of enhancement and C shows region of absorption of the optical probe field in the presence of the microwave field.

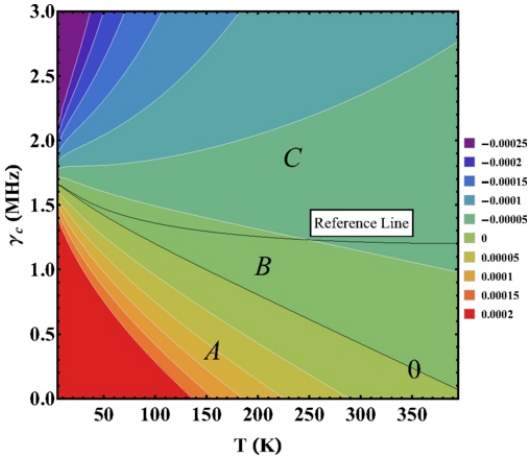


Fig.1[Image Credit: Manukumara Manjappa, Satya Sainadh Undurti, Asha Karigowda, Andal Narayanan, and Barry C. Sanders, (2014):Effects of temperature and ground-state coherence decay on enhancement and amplification in a ⊿ atomic system, Phys. Rev. A 90, 043859]

Coherent non-linear atom-optics in the low intensity regime is a feature unique to quantum optics of Electromagnetically Induced Transparency (EIT). Due to the elimination of linear order susceptibility due to quantum intereference, it is possible to induce higher order interaction in EIT systems with very low intensities. In the second broad research theme for the year 2014-2015, continuing with her in-depth analysis of Delta atomic configuration of levels in Rb. Atoms (Fig. 2) Narayanan and her group wanted to experimentally verify coherent microwave generation from the interactions of the two optical fields (w_p) and (w_c) within a high-finesse microwave cavity. Towards this, a very high Q microwave cavity has been built with the help of A. Raghunathan, (Radio Astronomy Laboratory, RRI).

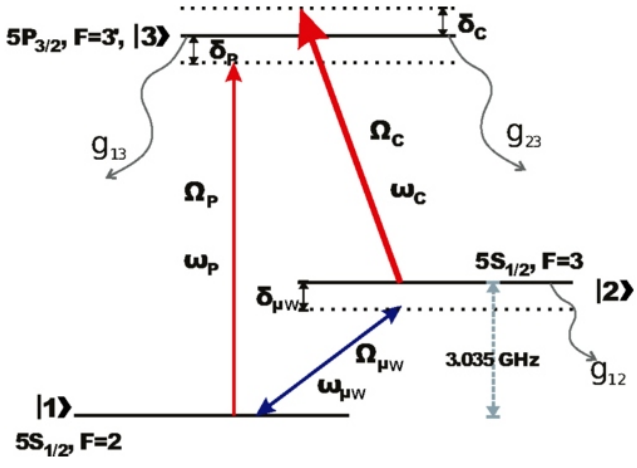


Fig. 2[Image Credit: Manukumara Manjappa, Satya Sainadh Undurti, Asha Karigowda, Andal Narayanan, and Barry C. Sanders, (2014):Effects of temperature and ground-state coherence decay on enhancement and amplification in a ⊿atomic system, Phys. Rev. A 90, 043859]

There are several fundamentally novel aspects to the microwave generation in Delta systems showing EIT. Any such generation will be the direct result of atomic superposition of ground states 1 and 2 (shown in Figure) during the dark state formation. Such a superposition will generate a Rabi oscillation in population shared by the ground states. The Rabi oscillations are connected with oscillating magnetic dipoles (as 1 and 2 are connected by a magnetic dipole transition) with a wavelength of about 10 cm (corresponding to 3GHz frequency). A very interesting question that is as yet unanswered is how non-linear interactions with optical fields whose wavelengths are about a micrometer in length can give rise to a coherent macroscopic magnetization of about 10 cm length! Along with Asha K. (Joint Ph.D student, Kuvempu University) and Harikrishnan A (Visiting Student, RRI) Narayanan hopes to see generation of microwaves in this system by inducing a dark state in Rb. atoms using optical fields within a high finesse microwave cavity.

The third topic of Narayanan's research during the previous year has been weak-value amplification in resonance fluorescence. Weak measurement refers to a measurement process on a quantum system by a measuring device, during which the system experiences very little perturbation. Aharonov, Albert and Vaidman first introduced this concept. It was pointed out subsequently that, under suitable conditions, a projective post-selection of the outcome of interaction can substantially alter the value of the measured observable from its value obtained by measurements without post-selection. For nearly orthogonal initial and final states, the weak value of the observable associated with the weak interaction can even get substantially amplified. Such an amplified value for the measured outcome of the observable due to post-selection is referred to as weak value amplification.

With an aim to clarify the precise sense in which weak value amplification effect seen in the resonance fluorescence spectrum from a V atomic system in an experiment conducted by I. Shomroni, O. Bechler, S. Rosenblum, and B. Dayan, Narayanan in collaboration with Satya Sainadh U, S. N. Sandhya (Miranda house, New Delhi) and Radhika Vathsan (BITS Pilani Goa Campus, Goa) have derived the mean transit time of atoms when the atom goes from an initial excited state to a designated final state using the well known Weiskopff-Wigner theory of spontaneous emission. Using this theory, they show that the extended excited state lifetime seen in the experiments by Shomroni *et al.*is the time associated with the atom changing from an initial superposition state configuration of excited states to another excited state configuration which is nearly orthogonal to the initial state. Since this is an elastic scattering event, this configuration change occurs without the decay of the atom to the ground state. In regular resonance fluorescence measurements without post-selection, atoms decaying from the excited state to the ground state dominate the scattering. We thus show that in this elastic scattering regime of resonance fluorescence, the weak value amplification effect has captured a rare event, which would have otherwise not been possible to observe. The simplicity of the theory allows its applicability to systems with multiple (more than two) excited states and allows for experimental observation of excited state configurational changes.

Hema Ramachandran's areas of current professional research interests include light propagataion in random media, few-atom and few-photon systems and brain-computer interfaces. Within the first research theme mentioned above, her research during the year gone by comprises of an important piece of work on real-time imaging through fog.

Scattering of light into a random direction is caused byan inhomogeneity in the dielectric constant of a transparent medium, on the length scale of a wavelength of light. The presence of a large number of such inhomogeneities leads to random multiple scattering, rendering transport of light through such a medium diffusive, rather than ballistic. This is what hinders imaging through tissues, and seeing through fog. Several techniques have been devised for extracting images in the presence of scattering – but they suffer from either the need for sophisticated equipment like streak cameras and femto-second pulsed light sources, or are computationally intensive. In the case of navigation under poor visibility, one would like image with a device that is inexpensive and portable, and one would like to view the images in real-time. For a continuous, flicker-free display, at least 30 frames need to be displayed per second, implying that data acquisition, processing, display and storage of an image (about a million pixels), should be completed within 30 milliseconds. This has not been possible to date. Hema in collaboration with Sriram Sudarsanam (Visiting Student, RRI), M.S. Meena (RRI), Swapnesh Panigrahi (University of Rennes, France), Julien Fade (University of Rennes, France) and Mehdi Alouini (University of Rennes, France), under the Project RITFOLD, partially funded by the Indo-French Centre for Promotion of Advanced Research, have now 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 was achieved by use of a software based quadrature-lock-in discrimination scheme and efficient parallelisation of computational tasks. Two tabletop experiments validated the applicability of this technique for use in navigation through fog. The results as illustrated in the following figures, have been submitted for publication.

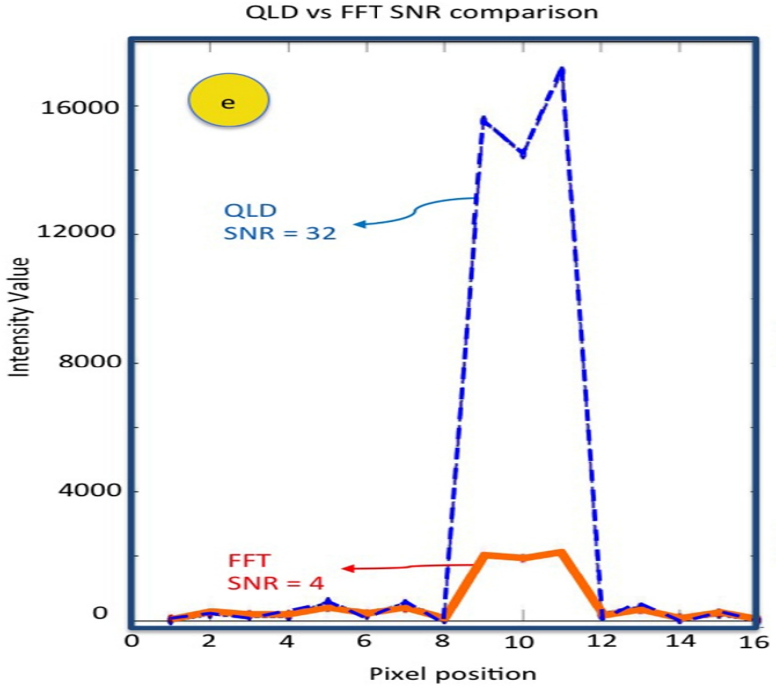


Fig. 1: Comparison of Quadrature-lock-in discrimination and Fast Fourier Transform performed on 256 raw frames to obtain a processed image. A better signal-to-noise ratio is obtained with QLD.

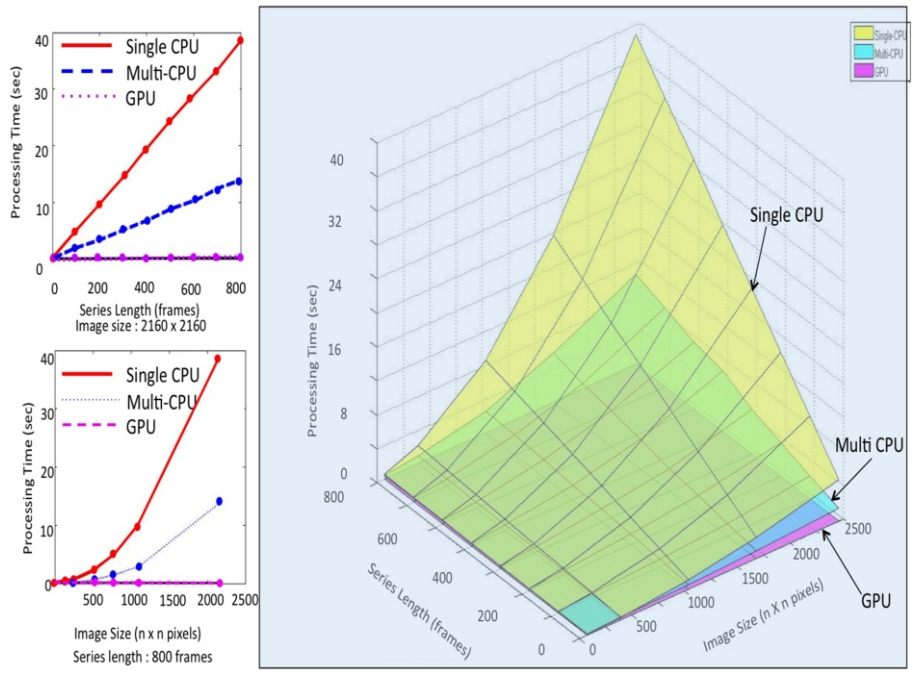


Fig. 2: Comparison of the processing times for QLD using a single CPU, multi-CPUand a GPU for computation.

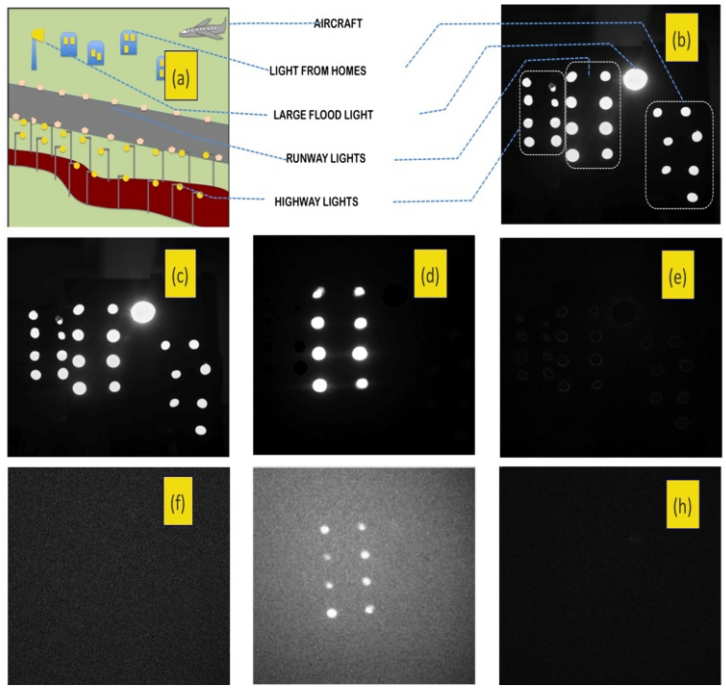


Fig.3: (a,b) The scene being simulated experimentally is one that has a variety of light sources. (c) The scene as it would appear to a pilot approaching for landing on a clear night. (d) Image obtained using QLD, where only the modulated runway lights are picked out. (e) No light source shows up when QLD is attempted at the incorrect frequency. (f) Typical view on a foggy night. (g) QLD at the correct frequency shows the runway lights. (h) QLD at the incorrect frequency does not show the light sources.

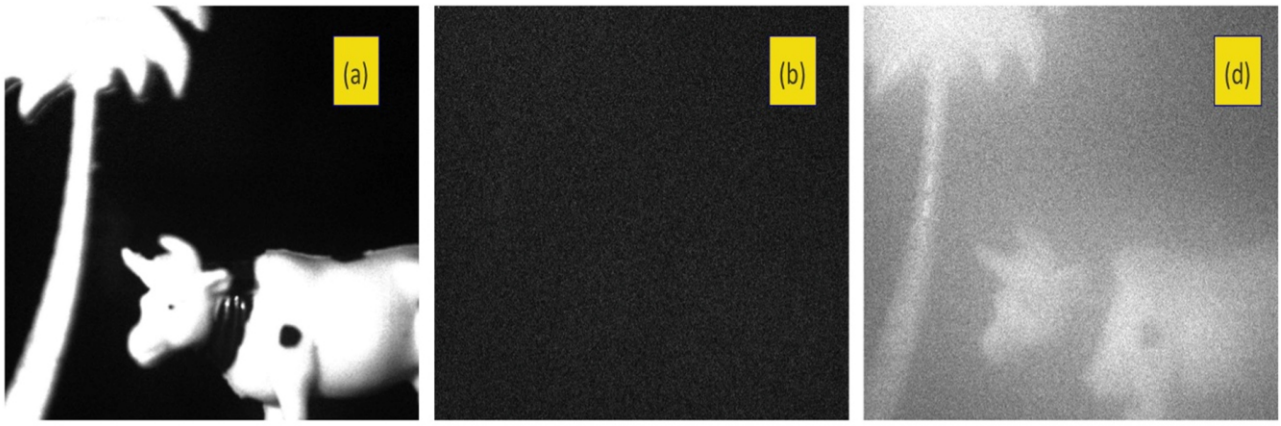


Fig.4: (a) Model of a tree and a cow, in the field of view. (b) A typical camera image when the tree and the cow are obscured by a strong scattering medium interspesed between the scene and the observer. (c) Upon QLD, the tree and the cow become visible.

The second broad research theme for Ramachandran during the year gone by has been a study of time-delayed intensity-interferometry of emission from laser-cooled atoms.

It is possible to determine whether a source of light is chaotic (thermal), or coherent, or quantum (eg. squeezed), by examining the arrival times of the photons. A thermal source of light tends to emit photons in a correlated manner – ie. it shows bunching of photons. A coherent source, like a laser, on the other hand, emits photons at random. A quantum source shows anti-bunching of photons. The correlation of photons is measured by the technique of time-delayed intensity interferometry. Photons from the source are directed through a beam-splitter, to one of two detectors (A, B), and the probability of a photon reaching detector B after an interval, t, of a photon having reached detector A, is measured. The correlation at zero delay (t = 0) helps determine the nature of the source while the correlation at non-zero delays reveals hidden periodicities.

Ramachandran along with Muhamed Shafi (Project Assistant, RRI), Deepak Pandey (University of Bordeaux) and G.S. Agarwal (Oklahoma State University, USA) have performed accurate measurements of the correlation function of emission from a collection of laser cooled atoms rubidium in a magneto-optical trap. Time-delayed-intensity-interferometry (TDII) performed with a 5-nanosecond time resolution yielded a second-order intensity correlation function that has the ideal value of 2 at zero delay, and that shows coherent Rabi oscillations of upto 5 full periods - much longer than the spontaneous emission lifetime of the excited state of Rb. The oscillations are damped out by ~ 150*ns*, and thereafter, as expected from a thermal source, an exponential decay is observed, enabling the determination of the temperature of the atomic ensemble. Values so obtained compare well with those determined by standard techniques. TDII thus enables a quantitative study of the coherent and incoherent dynamics, even of a large thermal ensemble of atomic emitters. This work has been communicated for publication.

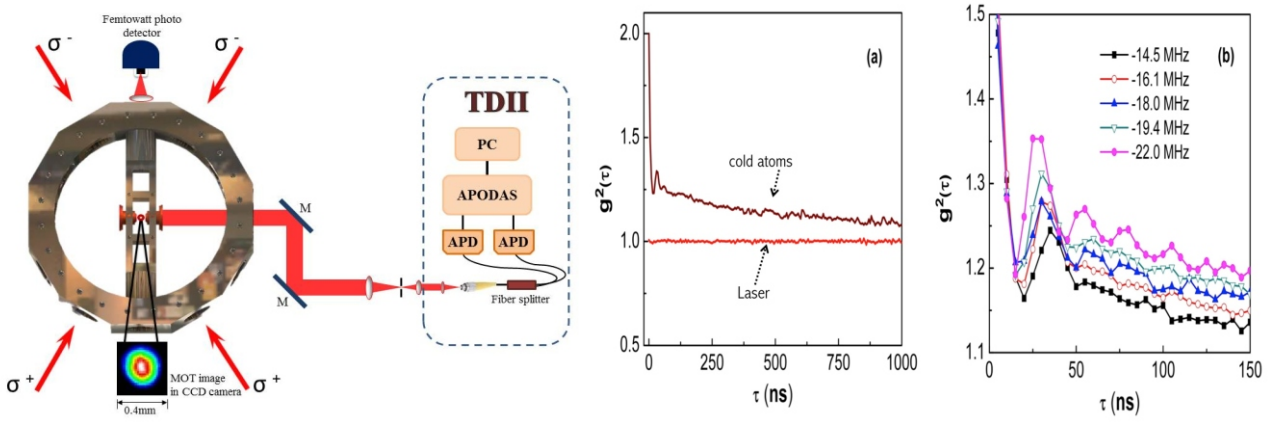


Fig.5: [Image Credit: Muhammed Shafi, Deepak Pandey, and Hema Ramachandran, (2014): Time-delayed Intensity-Interferometry with Light from Laser-Cooled Atoms, 12th International Conference on Fiber Optics and Photonics, OSA Technical Digest (online) (Optical Society of America), paper S5A.83.]

Brain computer interfaces constitute the third major research theme for Ramachandran. All our voluntary actions originate as electrical signals in the brain. Thus, the EEG (electro-encephalogram) should give us a clue of the intent of action of the subject. Extracting this information and driving devices based on it would then enable manipulation of machines using brain signals. This is a newly emerging field of study – that of Brain-Computer Interfaces. While this field initially started as means to help paralysed and locked-in persons, its immense potential has spurred research on applications to defense, navigation, surgery, robotics, industry, etc. In RRI, we have started it as a socially relevant project, where BCI may be used to enable some amount of independence in the paralysed, weak, ill or handicapped persons.

One of relatively easily detected signals is the steady-state visually evoked potential (SSVEP) – a potential in the occipital area, evoked by an external visual stimulus oscillating at a steady frequency in the range 10 to 20 Hz. SSVEP-based BCIs are the most studied. These typically have several LEDs blinking at different frequencies, and by assigning each LED to represent a certain task the subject on directing his attention towards one of the LEDs can initiate the corresponding task.

Hema and her collaborators – B. Ramesh, S. Sujatha, Sriram Sudarsanam, Somasekhar, K.B.R. Rao (all from RRI) and Visting students at RRI have together built in-house, a complete SSVEP-BCI system, that recognises the intent of the subject within 3 seconds, with and accuracy of higher than 90%. All components – the electrodes, the bio-amplifier, the digitisation module, the signal processing algorithms and the device drivers have been developed in-house. The entire unit is enclosed in a box 6" x 4" x 2", which also contains the battery that runs the system. The group is currently attempting to make it pocket-sized, and are targeting >95% accuracy before taking it for trial. A manuscript on this work is currently under preparation for publication.

Sadiq Rangwala's areas of current professional research interests include long range interactions in cold, dilute gas ensembles, stability of cold, trapped interacting mixtures, multiple collision physics between atoms and ions, light assisted collisions, atom-cavity interactions

and cavity QED processes. His present experiments focus on molecule-light and molecule-molecule interactions, atom-cavity physics and ultra-cold ion atom collisions.

During the year gone by, his research activities included an experiment on the phase sensitive radial extraction and mass spectrometry of trapped ions in a compact geometry. This work, published in Applied Phys. B. was done along with Jyothi S. and Tridib Ray (PhD students, RRI). In this paper, the detection of trapped atomic and molecular ions of Rubidium, by extraction, from the group's earlier designed thinwire electrode modified spherical Paul trap is discussed in detail. The compact geometry poses serious challenges and constraints for efficient extraction and reliable detection of ions. The solution to the dual challenge of counting the trapped ions with minimum pile up loss as well as detection that permits reliable mass spectroscopy has been experimentally implemented in this work. The details of the ion extraction process are understood by numerical simulation. The experimental and numerical data are compared and found to be in close agreement. The reliability of the technique for future, multispecies experiments, has been established and possible improvements discussed.

In another major piece of work, Rangwala in collaboration with Arijit Sharma, Tridib Ray, Rahul V. Sawant, G. Sheikholeslami, and D. Budker, has demonstrated the manipulation of transmitted light through an optical Fabry-Perot cavity, built around a spectroscopy cell containing enriched rubidium vapor. Light resonant with the ^{87}Rb D2 $(F=2/F=1) \leftrightarrow F'$ manifold, is controlled by 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 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. Both the steady state and transient response are experimentally investigated and the mechanism behind the change in cavity transmission has been discussed in this work that has been accepted for publication by Phys. Rev. A.

Along with Rahul Sawant (PhD student, RRI) Rangwala has also theoretically investigated optical bi-stability enabled control of resonant light transmission for an atom-cavity system. This explains the control of light transmission through a Fabry-Perot cavity containing atoms, 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 time dependent cavity field and atomic state populations. The conditions for optical bi-stability of the atom-cavity system are obtained in steady state limit. For an ensemble of atoms in the cavity mode, the response of the intra-cavity light intensity to the intersecting resonant beam is understood for stationary atoms (closed system) and non-static atoms (open system). The open system is then modelled by adjusting the atomic state populations to represent the exchange of atoms in the cavity mode, with the thermal environment. The solutions to the model are used to qualitatively explain experimentally observed steady state and transient behaviour of the light in the cavity mode, seen in Sharma *et. al.* The atom-cavity system, with three- and two-level atomic systems are also considered, and the rich physics arising out of the multi-level atomic systems, with closed and open atomic systems is discussed.

In addition, Niranjan Myneni (PhD student, RRI) and Rangwala have also pursued

research in a series of problems:

(i) A Virial theorem analysis of multipole ion traps - They have utilized the virial theorem to address one of the central problems of ion trapping and hybrid trapping experiments. The question they answer pertains to which is the optimal ion trap design for getting to the lowest ion kinetic energies. The answer is given by a direct argument using the virial theorem as well as numerical simulations. The virial analysis is found to be readily applicable to the driven and damped ion atom system. The analysis identifies suitable trap configurations to be used in the various applications with trapped ions.

(ii) Several detailed numerical studies have been performed to evolve a strategy to experimentally study ultra-cold ion-atom collisions, with the goal of reaching the s wave limit in ion atom collisions. Based on these studies, an experimental apparatus is on the verge of construction in a new laboratory, which is being constructed. This work represents a completely original approach to the ion-atom systems where the original concept to experimental implementation will be done at RRI.

Apart from these problems, manuscripts are under preparation for two other projects that Rangwala has been involved in during the past academic year.

(i) Creation and destruction of cold molecular ions in collaboration with S. Jyothi, Tridib Ray, Sourav Dutta (RRI), Rahul Sawant, Niranjan Myneni and Olivier Dulieu. In this experiment they have created a long bond molecular ion of Rb_2^+ from a magneto - optical trap of Rb atoms, by two photon excitation from highly excited vibrationally ground electronic molecular states. It is found that the resulting molecular ions decay quite rapidly in the hybrid trap, whereas the expectation would be that they are quite stable. It is then experimentally determined that the destruction of the ions is due to the presence of MOT light. The processes that might lead to photo-disintegration of the molecular ion have been calculated and the possible mechanisms are being determined. Once the mechanism is known they plan to learn how to trap molecular ions stable with cold atoms in their trap.

(ii) Normal mode splitting for higher order cavity modes in a coupled atom-cavity system, in collaboration with Niranjan Myneni, Sourav Dutta, Tridib Ray, Rahul Sawant and S. Jyothi.

Along with Sourav Dutta, another experiment on state selective collision rate measurement in ion-atom mixtures is underway, where they measure the survival of Rb^+ ions in contact with cold MOT atoms. In a fluorescing MOT, the atoms are in a mixture of ground and excited states. In the present experiment, they have created a dark MOT, which results when the cold atoms are optically pumped into the ground state which is not in the MOT cooling cycle. In this case, the atoms are in a specific quantum state and the cooling of ions in collision with the atoms is a state selective collision. On the other hand the collision of the ions with the bright MOT gives information on ion collision with atoms in a mixture of ground and excited states. The difference in the collision rate between the dark MOT and the bright MOT would give the collision rate with atoms in the excited state.

Urbasi Sinha's areas of current professional research interests are quantum information, quantum computation and quantum communication using single photons and experiments on quantum foundations. During the year gone by she has completed research in four major pieces of work largely on the theme of Quantum Foundations and

Quantum Information Theory.

The first major result from her group was a more complete understanding of the limitations of the application of the superposition principle in slit based interference experiments. This work was published this year in *Physical Review Letters* and was selected for a focus article in *Physics*.

In a 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 directly applicable. However, most well known textbooks in quantum mechanics implicitly and/or explicitly use this assumption that is only approximately true. In her recent work, in collaboration with Rahul Sawant, J. Samuel and S. Sinha (RRI) and A.Sinha (IISc, Bangalore), Urbasi has 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. Although a direct experimental demonstration for the existence of these non-classical paths is difficult to present, they find that contributions from such paths can be significant and propose simple three-slit interference experiments to directly confirm their existence. The contributions of such paths are quantified in terms of the normalized version of the Sorkin parameter and the work provides the first theoretical bound on this quantity. The calculations also imply that the deviation can be measured in slit based tabletop experiments.

The second result is an analytic understanding of the above problem. The PRL paper considered numerical simulations based on path integral formalism. In her more recent work, Urbasi has been able to derive an analytical formula for the normalized Sorkin parameter, which she calls "kappa". This analytic closed form expression is not only important from a theorist's point of view but also gives her a handle on the parameters determining kappa experimentally. This analytic handle now makes it easier to "design" experiments in which kappa can be big and hence more easily measurable. What is beautiful about the analytic formula is that it gives Urbasi and her collaborators in this project, Aninda Sinha (IISc, Bangalore) and Aravind H.V, an excellent match with simulations of Maxwell 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, their analytic formula can be computed within seconds using standard softwares like *Mathematica* on a laptop. This work has been published in *Nature Scientific Reports*.

The third result involved collaborating with the Institute for Quantum Computing (IQC), Waterloo, Canada. The experiment was done at IQC. Envariance, or environment-assisted invariance, is a recently identified symmetry for maximally entangled states in quantum theory with important ramifications for quantum measurement, specifically for understanding Born's rule. In this work, Urbasi and her collaborators, Lydia Vermeyden, Xian Ma, Jonathan Lavoie, Madeleine Bonsma, Raymond Laflamme and Kevin Resch of IQC, have benchmarked the degree to which nature respects this symmetry by using entangled photon pairs. The results show quantum states can be 99.66(4)% envariant as measured using the quantum fidelity, and 99.963(5)% as measured using a modified Bhattacharya Coefficient, as compared with a perfectly envariant system which would be 100% in either measure. The less-than-

maximal entanglement in the photon pairs used is the reason behind the observed deviation. This work has been published in *Physical Review A*.

The fourth result involved a theoretical work on the concept of weak measurements. In quantum theory, a Hermitian operator represents a physical observable, as it admits 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 an operator does not mean that it is necessarily Hermitian. There are examples of non-Hermitian operators that 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, Urbasi along with Arun Pati and Uttam Singh(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 this for the creation and annihilation operators and the Kraus operators. This is under review in *Physical Review A*.

As far as experiments are concerned Urbasi has successfully set up the Quantum Information and Computing lab at RRI, which involved setting up for the first time in our country, an optics lab which also boasts of a "clean room" environment. The optics lab has a class 10000 clean room environment which involves control of temperature, humidity and dust - level through precision air handling systems to enable precision experiments based on interferometry and the production and application of heralded single photon sources and entangled pair photon sources.

Sinha and her group have also recently acquired a tunable Ti-Saphire laser system from Coherent Inc. This is only the second such system at RRI. They are currently using this for their experiment on detecting non-classical paths. A picture of the experimental set-up is included below in Fig. 1. Sinha and Debadrita Ghosh (Project Assistant, RRI) and Surya Narayan Sahoo (PhD student, RRI) are doing this experiment.

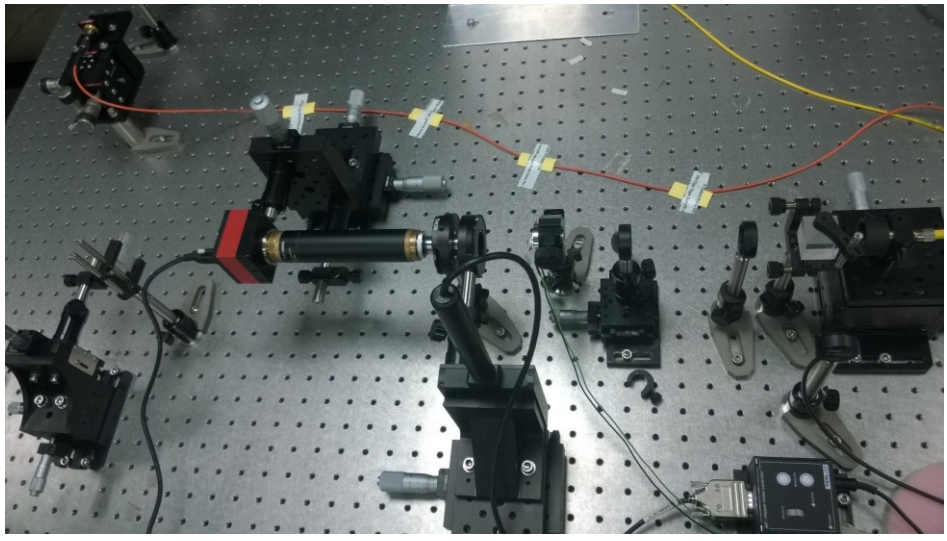


Fig.1: A picture of the experiment to detect non-classical paths in quantum interference experiments

The other major experiment that Sinha has undertaken this year involves collaboration with a radio-astronomy lab at RRI of Ravi Subrahmanyan and Udaya Shankar. This is a microwave version of the above experiment and involves usage of horn antennas, spectrum analyzers and home built slots and slot stands. This experiment is being done partly at RRI and partly at the Gauribidanur field station of the Institute. The current version of the experiment, which was arrived at after several steps of noise and error analysis, is being conducted in collaboration with Rengaraj Aparijathan, (Visting student, RRI) and currently a project assistant at IISc. A version of the set-up figure is included below in Fig. 2.



Fig. 2: A preliminary set-up for the microwave version of the experiment to detect non-classical paths in interference experiments

A major experimental achievement for the lab in the academic year 2014-2015 has been the establishment of both Type I and Type II single photon sources. Single photon sources are sources that emit light as single particles or photons. Although attenuating laser light may lead to sources of few photons, these are statistically different from single photon sources based on spontaneous parametric down conversion (SPDC). These sources give rise to an effectively one-photon number state and thus exhibit truly quantum characteristics. Single photon sources are ubiquitous in their applications in quantum mechanics, quantum information and quantum communication experiments. A major thrust of the lab has been in the development of different types of sources for such purposes.

There are different types of SPDC sources, which depend on what are called phase matching conditions. The photons are emitted as pairs and the equations, which govern SPDC dictate that the emitted photons have trajectories that are constrained to be within cones. If both photons emitted in a pair have the same polarization (opposite to the pump photon), it forms what is called a Type I source. The bi-photon state in a Type I source represents a certain Bell state. Then the photons are emitted as overlapping cones. Again depending on whether these photons follow collinear or non-collinear geometry, the cone can be shrunk to a point or not. Type I SPDC cones from Urbasi's lab are shown in Fig. 3.

When both photons have opposite polarization to each other, then they form a Type II source. The bi-photon state in a Type II source represents a different Bell state. Photons at the point of intersection of the cones could belong to either cone and thus cannot be represented by a product state, forming instead an entangled state. Type II SPDC cones are shown in Fig. 4.

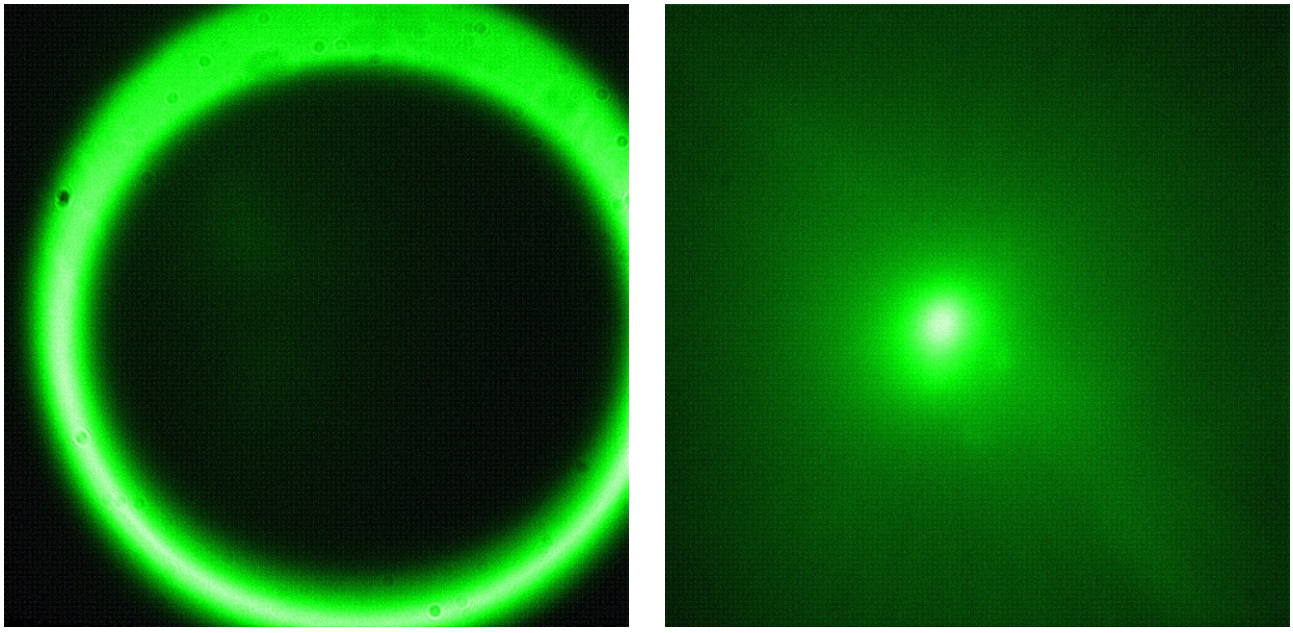


Fig. 3: Down conversion rings from the Type I source in Sinha's lab. Figure on left shown non-collinear configuration while figure on right shown collinear configuration.

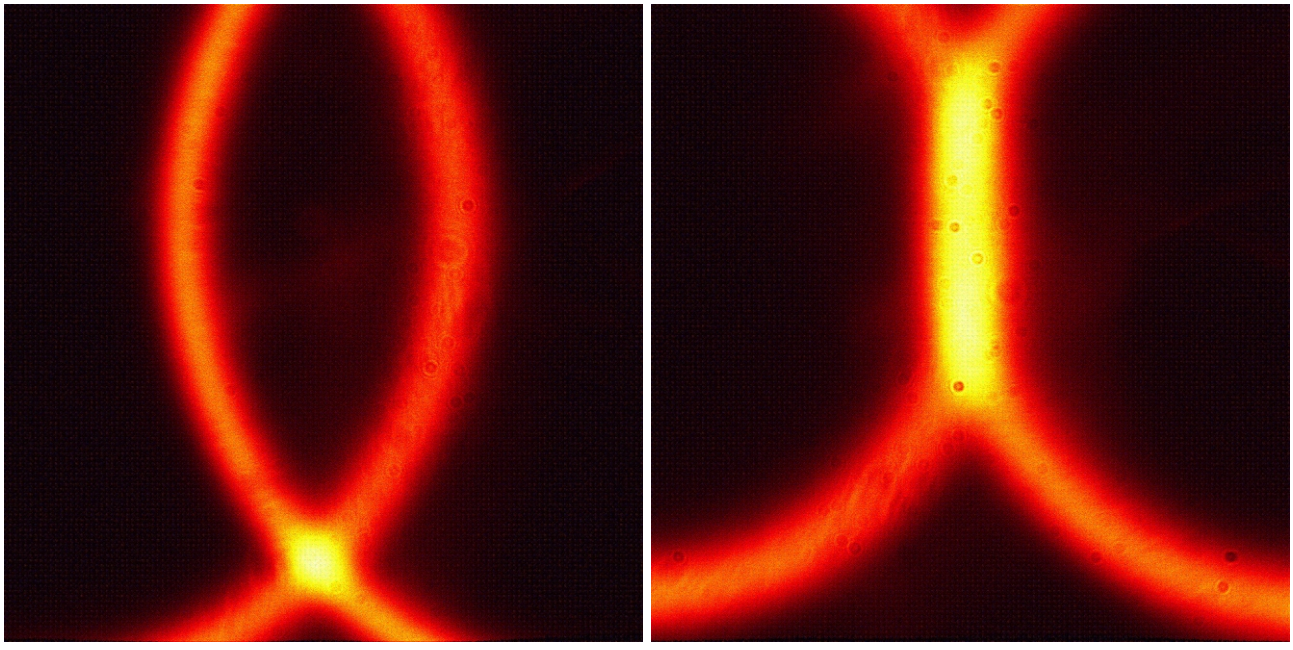


Fig. 4: Down conversion rings from the Type II source in Sinha's lab. Figure on left shows the non-collinear configuration. Figure on right shows the collinear configuration. The point of intersection of the two cones signifies an entangled state.

The final experimental project that Sinha and her group have embarked upon in the last year has been that of inferring expectation values of Non-Hermitian operators using the concept of weak interaction. This is the experimental realization of the theory proposal that Sinha has developed with Arun Pati (HRI, Allahabad) and his student Uttam Singh, mentioned earlier. The project involves setting up of a stable Mach Zehnder interferometer and performing various operations therein. This experiment is being performed in collaboration with Sudhi Oberoi (Visiting student, RRI) and Debadrita Ghosh, (Project assistant, RRI).

Sourav Dutta's research interests focus on Cooling and trapping of ultracold atoms, ions and molecules; Photo association of ultracold homonuclear and heteronuclear molecules; Optical manipulation of atoms, ions and molecules; Cavity based detection of interactions.

Sourav is primarily interested in the physics and chemistry of atoms, ions and molecules at ultralow temperatures. His work centres on cooling and trapping of atoms, ions and molecules in order to study cold collisions and interactions at low temperatures. At ultralow temperatures, collisions can no longer be described classically making cold collisions ideal for the study of quantum mechanical scattering. He and his collaborators have recently created ultracold molecules by photo association and molecular ions by multi-photon ionization, and are currently studying the properties of trapped molecular ions. They are also interested in devising new experimental techniques for detection and manipulation of interactions between atoms, molecules and ions - one such technique specifically being pursued is cavity based detection of ion-atom interaction.

During the period 2014-2015 Dutta's research focused on the following themes:

i) Production of Rb_2^+ by Resonance Enhanced Multi Photon Ionization (REMPI): Creating Rb_2^+ by ionizing Rb_2 molecules produced via photo association (PA) was tried in the past by Sadiq Rangwala's lab. However, these efforts were unsuccessful because photo associated Rb_2 molecules near the Rb D_2 asymptote were prone to predissociation, a fact evident from the observed PA line widths of around a GHz. Dutta and his collaborators tried a different method to produce Rb_2^+. In a *Rb* Magneto-optical trap (MOT) a few ground state Rb_2 molecules are formed by PA due to the *Rb* trapping laser followed by spontaneous decay. These ultracold Rb_2 molecules could be ionized with a pulsed dye laser to form cold Rb_2^+ ions. The pulsed laser when tuned to a specific wavelength (λ = 602 nm) efficiently produces cold Rb_2^+ ions by REMPI of Rb_2 molecules. This allowed Rb_2^+ ions to be produced and detected for the first time at RRI. These results form a crucial element of the paper entitled "Phase sensitive radial extraction and mass spectrometry of trapped ions in a compact geometry" by S. Jyothi, T. Ray (PhD students, RRI) and S. A. Rangwala (RRI).

ii) Effect of MOT cooling light on trapped Rb_2^+ molecular ions: Dutta and his collaborators have 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.

They have observed that the presence of the *Rb* cooling laser beam reduces the lifetime of Rb_2^+ ions dramatically. One possible explanation is that the *Rb* cooling light dissociates the Rb_2^+ ions. The photodissociation of Rb_2^+ ion may proceed via a single photon or a multi-photon process. Three possible pathways are presently under consideration:

(i) A single 780 nm photon excites the Rb_2^+ ion to a dissociating electronic state,

(ii) Simultaneous absorption of two 780 nm photon leading to photo dissociation, and

(iii) Repeated off-resonant absorption and spontaneous emission of photons that shift population to higher and higher vibrational levels, ultimately leading to dissociation of the Rb_2^+ molecular ion. This work is done in collaboration with S. Jyothi and S. A. Rangwala, and a manuscript (S. Jyothi *et al*.) reporting the results is currently under preparation.

(iii) Implementation of dark spot Rb MOT and studies on the effect of electronically excited Rb atoms on ion-atom collisions: In a traditional bright Rb MOT, a large fraction (~ 15-25%) of the atoms is in the excited 5p state while the rest are in the ground 5s state. Dutta has worked on implementing a dark spot Rb MOT in which most (~ 99%) of the Rb atoms are in the ground 5s (F = 2) state with negligible population in the excited 5p state. In addition, by varying different parameters in the experiment one can control the fraction of excited state atoms. This led to an investigation into whether the lifetime of the Rb^+ ions, trapped in presence of ultra cold Rb atoms, depend on the electronic state of the Rb atoms. At large atomic densities, they have observed only negligible dependence on the electronic state of the Rb atoms. This is counter intuitive to the notion that the higher cross section of the 5p state should lead to longer lifetimes. However, at low atomic densities, they have observed, as expected, a significant dependence of the Rb^+ ion lifetime on the electronic state of the Rb atoms. Currently they are trying to model and understand this density dependence. In a related work, they have already observed that under a certain condition (large atomic density and small number of ions) ions can remain trapped with near unit efficiency for durations exceeding a minute – this may suggest cooling of ions to extremely low temperatures. This work is done in collaboration with S. A. Rangwala, and a manuscript (S. Dutta et al.) reporting the work is currently under preparation.

(iv) Vacuum Rabi Splitting (VRS) measurements in a dark MOT: The implementation of the dark MOT opened up the possibility to do continuous VRS measurements on ultra cold atoms coupled to a Fabry-Perot cavity. 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. Dutta and Rangwala's lab have also demonstrated a new technique based on VRS 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. They have also experimentally demonstrated the dependence of VRS on higher order cavity modes.

A closer look at VRS measurements done with different probing light intensities has showed that VRS decreases with

increasing probe intensity. The measurements also revealed an asymmetry in line shape of the vacuum-Rabi peaks – a possible signature of optical bi-stability. Dutta also noticed that the vacuum-Rabi peaks disappear (or become much smaller in intensity) when ~15 μW of light (blue detuned by 29 MHz from the $F = 3 \rightarrow F' = 3$) is incident on the atoms from a transverse direction. This phenomenon is reminiscent of an optical switch and it may be of interest to pursue this experiment further.

(v) Stabilizing lasers by locking to high finesse optical cavity: Dutta has also worked on stabilizing a laser (852 nm Toptica DL-pro) by locking it to a high finesse optical cavity using the Pound-Drever-Hall method. The line width of the cavity transmission is measured to be around 600 kHz and the lock could be maintained for tens of minutes. The same technique was used to lock a 780 nm laser to the cavity within the vacuum chamber. This technical development is expected to enable new research.

(vi) Formation of ultracold LiRb molecules in the triplet ground state by photo association (PA): This work was done by Dutta in collaboration with Adeel Altaf, John Lorenz, Jesús Pérez-Ríos, Yong P. Chen and Daniel S. Elliott (Purdue University, USA). In this work, published in the *Journal of Chemical Physics* 142, 114310 (2015), they have reported the formation of ultracold LiRb molecules in the triplet ground state by photo association (PA) and their detection via resonantly enhanced multi photon ionization (REMPI). They have used REMPI spectroscopy to probe the ground triplet $\alpha^3\Sigma^+$ state and the excited electronic $3\,^3\Pi$ and $4\,^3\Sigma^+$ states. These spectroscopic studies on previously unobserved electronic states are crucial to discovering transition pathways for transferring ultracold LiRb molecules created via PA to deeply bound vibrational levels of the electronic ground state.

(vii) Formation of deeply bound ultracold LiRb molecules via photo association near the Li $2S_{1/2}$ + Rb $5P_{3/2}$ asymptote: This work, done in collaboration with John Lorenz, Adeel Altaf, Yong P. Chen and Daniel S. Elliott (Purdue University) has been published in *Physical Review A* 90, 062513 (2014). The paper presents the spectra of LiRb molecules in their electronic ground $X^1\Sigma^+$ state formed by spontaneous decay of weakly bound photo associated molecules. Beginning with atoms in a dual species magneto-optical trap (MOT), weakly bound molecules are formed in the 4(1) electronic state. These molecules spontaneously decay to the electronic ground $X^1\Sigma^+$ state and once again, they use REMPI method to determine the vibrational population distribution in the $X^1\Sigma^+$ state. It is observed that deeply bound vibrational levels with vibrational quantum number v'' as low as $v''=2$ are populated. Deeply bound polar molecules, especially in $v''=0$, are of tremendous interest for quantum simulations and quantum computing. They have also deduced a lower bound of 3900 cm^{-1} for the dissociation energy of the $LiRb^+$ molecular ion.

(vii) Two-photon photo association of LiRb: In this paper Dutta has worked on understanding and interpreting the observations during two-photon PA of LiRb molecules in collaboration with Jesús Pérez-Ríos, Yong P. Chen and Chris Greene (Purdue University). The results have recently been published in a *Focus Issue of the New Journal of Physics* 17, 045021 (2015). This work is the first demonstration of two-photon PA in heteronuclear alkali molecules with dipole moment and also shows that multi-channel quantum defect theory is a useful tool in understanding such spectra.

(viii) Extracting molecular potentials from incomplete spectroscopic information: This work was done in collaboration with Xuan Li (Lawrence Berkeley National Laboratory,

USA). In this work, accepted for publication in Molecular Physics, Dutta and Li have extended a recently developed inversion method to extract excited state potentials from fluorescence line positions and line strengths. They consider a previous limitation due to insufficient input data where the relatively weaker emission data are not experimentally available. "Regenerating" these weak transition lines via applying a model potential, e.g. a Morse potential, leads to the solution to this problem. The robustness of this procedure is also demonstrated in the paper by considering the statistical error in the measured line intensities.

M. Anil Kumar's areas of current professional research interests lie predominantly in Quantum Optics, Optomechanics and Foundation of Quantum Mechanics. During the past year, his research activities concentrated on taking an optomechanical system and theoretically investigating how quadratic optomechanical coupling (QOC) presence with the conventional linear optomechanical coupling (LOC) affects the Optical quadrature Squeezing, mechanical oscillator Squeezing, Entanglement between cavity and mechanical modes, Normal mode splitting and Optomechanical cooling. His collaborator in this project was U. Satya Sainadh (Griffith University, Brisbane).

Given the importance of Optical quadrature squeezing in the field of metrology, it is very important to be able to answer how much these couplings (LOC and QOC) together can affect it. Anil Kumar and Sainadh have constructed a Hamiltonian for the optomechanical system, where the optical field inside the cavity couples to the mechanical oscillator via linear and quadratic displacements and there exists an optomechanical coupling LOC (g_1) and QOC (g_2) in the system. Using this Hamiltonian, they have then constructed the equations of motion which when solved under steady state conditions generate an expression for the mean number of photons ($\bar{n}$) in the cavity. Also they have constructed equations of motion for small fluctuations, using which one can deduce stability of system and as well as the expression for Optical quadrature Squeezing (S_{opt}). Figure 1 shows how the Optical quadrature squeezing spectrum (S_{opt}) varied as a function of normalized frequency (w/w_m) at 1 mK as the bath temperature and 100 micro watt pump power. The black curve represents the squeezing due to LOC alone whereas blue, green orange and red corresponds to squeezing due to different QOC. Higher squeezing is obtained in presence of QOC as compared with LOC and it is observed that the frequency at which squeezing occurs changes with QOC values.

They have observed that the effect of QOC is remarkable in that even at a value as less as 1/100 times of LOC it can aid in enhancing squeezing thrice (~ 60%) as much as its LOC counterpart (~ 20%). They have analyzed and compared a cavity optomechanical system containing both LOC and QOC together to a system with LOC alone. In doing this, they observed that the inclusion of QOC to a conventional LOC optomechanical system shrinks the stability range and can aid in higher squeezing at lower powers and higher bath temperatures. They also found that at a particular bath temperature, having higher value of QOC does not necessarily lead to higher percentage of achievable squeezing. There has to be a trade-off between the QOC and the stability range such that one can maximize the squeezing. Unlike the hybrid-optomechanical system, the system under study is advantageous as one can preserve all the capabilities of controlling the level of squeezing without introducing any extra degrees of freedom. The system with both LOC and QOC interactions can be a good platform for achieving higher squeezing and

can be used in realizing better quantum mechanical devices.

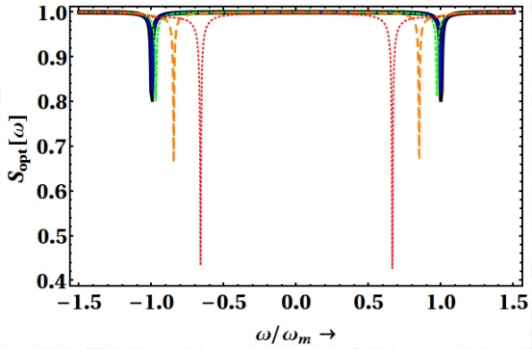


Fig.1: Squeezing spectrum for Optical quadrature field plotted as function of normalized frequency (ω/ω_m) for an optomechanical system with different QOCs. The system parameters are $\Delta = \omega_m$, T=1mk, and P = 100 micro Watt. The curve black, blue, green, orange and red corresponds to QOC, as $\frac{g_2}{g_1} = 0, -10^{-4}, -10^{-3}, -5\times10^{-3}$ and -10^{-2}, respectively with $g_1 = 1351.38\,Hz$.





SOFT CONDENSED MATTER

Overview

Soft materials, constituted by molecules that are held together by weak inter-macromolecular forces, are characterized by complex structures and phase behaviour. Colloidal suspensions and emulsions such as milk and paint, polymeric and biological materials, foam, and liquid crystals are some common examples. The size of the molecules that constitute these materials is 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 103 seconds. The structure and dynamics of these materials can therefore be easily studied using relatively simple laboratory techniques. Characterized by elastic constants that are many decades lower than those of traditional atomic solids, soft materials are viscoelastic and can be used in the study of a variety of non-equilibrium phenomena. Inter-constituent interactions can be easily modified in soft materials; a feature that is particularly suitable for engineering new materials with interesting and useful properties. Their structural complexity and mechanical flexibility make soft materials ideal for many applications. Moreover, soft matter systems are a testing ground for theories and models of statistical physics.

The soft condensed matter group at RRI is engaged in research on liquid crystals and their chemical synthesis, colloids, polymers, nano-composites, amphiphilic systems, physics and chemistry of surfaces, and biological physics.

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, electric, and magnetic fields. Among these soft materials, thermotropic liquid crystals consisting of highly anistropic organic molecules, nano-composite materials, polymers and biomaterials such as biomolecules and cells are 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.

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. A number of monomeric, oligomeric, polymeric, and ionic liquid crystalline materials have been synthesized. 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.

The incorporation of nanomaterials like metal-nanoparticles, quantum dots, carbon nanotubes and graphene 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 other molecules and disperse them in monomeric, oligomeric and polymeric discotic liquid crystals. The dispersion of such functionalised nanomaterials in columnar matrix has been found to enhance physical properties such as conductivity and photo conductivity significantly.

One of the present research interests of the SCM group is in investigating electric field induced chiral symmetry breaking in liquid crystals made of achiral molecules. The structure and properties of novel field induced dark mesophases 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 enantioselectivity. The role of growth morphology in coarsening is under study to get a physical insight into the effects of chiral and electrostatic interactions. Studies of chiral thin films possessing tunable enantioselectivity are also interesting from a technological point of view, as they have potential for chiroptical and NLO applications.

Another area of interest is in understanding structure and dynamics of polyelectrolytes using dielectric spectroscopy. Very low frequency relaxation modes arising from polarization mechanisms involving counter ions and polar side chains are usually quite challenging to probe experimentally, and have therefore not been explored extensively. Detailed dielectric studies have been undertaken on some aqueous polyelectrolytes, some of which also

exhibit coacervation.

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.

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.

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, 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.

Biophysics

The Biophysics group at RRI encompasses experimental, theoretical and computational study 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 signalling at 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 which help in deciphering secrets of biological nano-world and ultra-sensitive force measurement methods to probe mechanical responses of single cells. Theoretical and computational approach is aimed at not only deciphering quantitative experiments but also to predict novel mechanisms. This is a rapidly expanding area of research at RRI and overlaps with other traditional topics like statistical mechanics, membrane- and polymer physics.

Theoretical studies

Theoretical investigations in the SCM group primarily focus 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. This is also the case for certain smectic liquid crystals, and thin crystalline lamellae. For example, solution- and melt grown polymer crystallites grow in the form of lamellae exhibiting diverse morphologies such as helicoidal-, 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 areas of professional research interests currently lie in structure, dynamics and rheology of non-Newtonian fluids, aging and soft glassy rheology, flow-structure correlations in complex fluids, micellar packings, controlled, 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.

During the period 2014-2015, Ranjini along with Rajib Basak, (PhD student, RRI) have studied the formation and rupture of Ca^{2+} induced pectin bio-polymer gels. When calcium salts are added to an aqueous solution of polysaccharide pectin, ionic cross links form between pectin chains, giving rise to a gel network in dilute solution. In this work, dynamic light scattering (DLS) is employed to study the microscopic dynamics of the fractal aggregates (flocs) that constitute the gels, while rheological measurements are carried out to study the process of gel rupture. As the calcium salt concentration is increased, DLS experiments reveal that the polydispersity of the flocs increases simultaneously with the characteristic relaxation times of the gel network. Above a critical salt concentration, the flocs become interlinked to form a reaction limited fractal gel network. Rheological studies demonstrate that the limits of the linear rheological response and the critical stresses required to rupture these networks both decrease with the increase in salt concentration. These features indicate that the ion-mediated pectin gels studied in this work lie in a 'strong link' regime that is characterised by interfloc links that are stronger than intrafloc links. A scaling analysis of the experimental data demonstrates that the elasticities of the individual fractal flocs exhibit power-law dependencies on the added salt concentration. We conclude that when both pectin and salt concentrations are increased, the number of fractal flocs of pectin increases simultaneously with the density of cross links, giving rise to very large values of the bulk elastic modulus.

The second broad research theme for Ranjini during the previous year has been that of a dynamic light scattering study and DLVO analysis of physicochemical interactions in colloidal suspensions of charged disks – a work in which she collaborated with Debasish Saha, (PhD student, RRI) and Yogesh M. Joshi, (IIT Kanpur). In this study they have investigated the inter-particle interactions in a colloidal suspension of charged disks of Laponite clay in water using dynamic light scattering (DLS) and Derjagiun-Landau-Verwey-Overbeek (DLVO) theory. The effects of clay concentration (C_L), the concentration of externally added salt C_s and temperature (T) on the microscopic dynamics of clay suspensions have been studied.

The fast and slow relaxation times of suspensions of Laponite, (synthetic clay), are extracted from intensity auto correlation functions measured at different waiting times (t_w) since sample preparation. Comprehensive overlaps of the microscopic diffusive dynamics time scales of clay suspensions with C_L, C_s, T and t_w are obtained for both the fast and the slow relaxation time scales. The results reported in this work highlight the self-similar nature of the energy landscapes of Laponite suspensions when C_L, C_s and T are changed. The evolutions of the sodium ion concentration with waiting time are also measured for several values of C_L, C_s and T.

Ongoing Research

The DLVO theory is employed to compute the free energies of Laponite suspensions to understand the observed self-similar evolution of the relaxation timescales. In addition to repulsive inter-particle interactions, the influence of attractive interactions is also clearly observed for the younger spontaneously evolving Laponite suspensions that have been studied in this work.

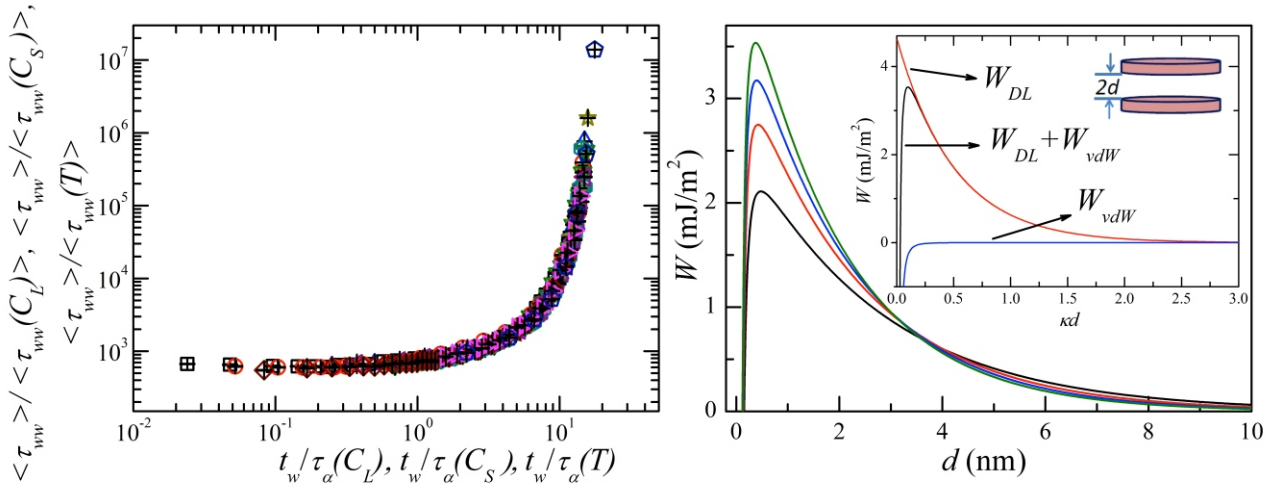


Fig.1: [Image Credit: Saha D;Bandyopadhyay R;Joshi Y. M. (2015): A Dynamic Light Scattering Study and DLVO Analysis of Physicochemical Interactions in Colloidal Suspensions of Charged Disks, Langmuir 31 (10), 3012–3020]

Ranjini Bandyopadhyay has also worked on the evaluation of the exfoliation and stability of natural clay in aqueous dispersions in collaboration 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 time and concentration dependence of the exfoliation process plays an important role in the dispersion behaviour of clays and has been studied experimentally by the same group in a preceding article [Langmuir, 2013, **29**, 12663-12669]. This study focuses on the effects of screened Coulomb repulsions and the osmotic pressure of the Na^+ counter ions on the exfoliation of natural clay tactoids. Using ultrasound attenuation spectroscopy, the degree of exfoliation (the dispersibility) of tactoids at different clay concentrations, added salts and ages of the clay suspensions is estimated. 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 screened Coulomb repulsions become more dominant. Furthermore, the influence of clay dispersibility on the suspension stability behaviour of the arrested phases formed at different ionic conditions was studied by measuring the ultrasound induced colloidal vibration current.

With Debasish Saha, (PhD student, RRI) and Yogesh M. Joshi, (IIT Kanpur), Ranjini has also explored the kinetics of the glass transition of fragile soft colloidal suspensions. Microscopic relaxation time scales are estimated from the auto correlation functions obtained by dynamic light scattering experiments for Laponite suspensions with different concentrations C_L added salt concentrations C_S and temperatures (T). This group has shown in an earlier work [Soft Matter **10**, 3292 (2014)] that the evolutions of relaxation time scales of colloidal glasses can

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 the present work, the fragility parameter D, which signifies deviation from Arrhenius behaviour, is obtained from the fits to the time evolutions of the structural relaxation time scales. For Laponite suspension, D is seen to be independent of C_L and C_S, but is weakly dependent on T. Interestingly the behaviour of D is observed to corroborate the behaviour 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 time scales is seen to depend on t_w. Just as a Kauzmann temperature is defined for molecular glasses, a hypothetical Kauzmann time scale (t_k) is defined at which w diverges. Simultaneously, just as a Vogel temperature is defined in molecular glasses, a hypothetical Vogel timescale t_α^∞ is defined. Interestingly a correlation is observed between t_k and t_α^∞, which is remarkably similar to that known for fragile molecular glass formers. A coupling model along with t_w dependence of the stretching exponent is used to analyze correlation between t_k and t_α^∞ .

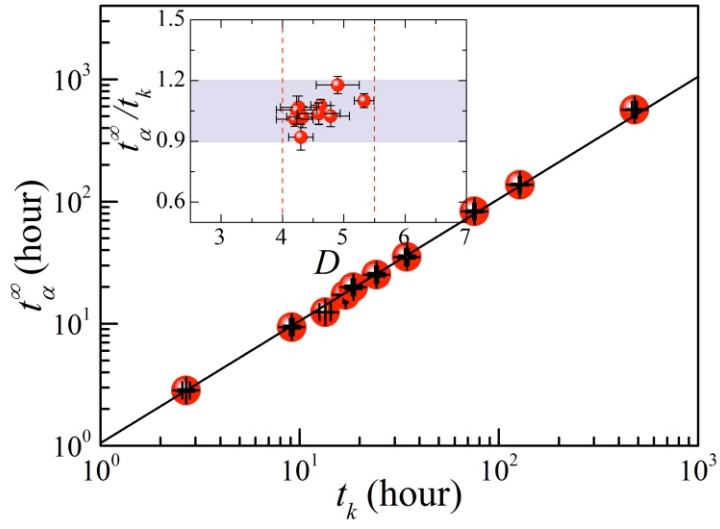


Fig.2: Plot showing correlation between Kauzmann time scale (t_k) and the Vogel time scale t_α^∞ in Laponite suspensions showing behaviour similar to that of fragile molecular glass formers.

The fifth broad research theme undertaken by Ranjini this previous year has been an exploration of the aggregation and stability properties of anisotropic charged clay colloids in aqueous medium in the presence of salt. Her collaborator in this work is Samim Ali (PhD student, RRI). Na-montmorillonite nano clay 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. The aqueous dispersion can exhibit a spontaneous ergodicity breaking phase transition from free flowing liquids to non-equilibrium, kinetically arrested and disordered states such as gels and glasses at low particle concentrations. The interactions between these charged platelets, and hence their assembly and stability behaviour, can be controlled externally by adding salt to the medium. Using optical and electroacoustic methods they have shown that colloidal gels of Na-montmorillonite platelets are not stable when salt is added to the medium before dispersing clay minerals. On the other hand,

addition of salt after dispersing the mineral produces weak gels. These weak gels are stable for a finite delay time before transient collapse under gravity. Moreover, the velocity is seen to increase linearly during transient collapse. This is followed by a gel compaction regime where the velocity of the gel-interface decreases exponentially. The delay time of the transient collapse decreases with increasing salt concentration and finally disappears at very high salt concentration. Using ultrasound attenuation spectroscopy, rheometry and cryogenic scanning electron microscopy, they have confirmed that morphological changes of the gel network assembly leads to transient collapse, with an enhancement in the aggregation of parallel-oriented platelets contributing to the observed increase in the velocity of collapse. Since clay minerals are being used extensively in polymer nano-composites as rheological modifiers, as stabilizers and as gas absorbents, the results reported in this work are extremely useful for several practical applications and also for understanding geophysical phenomena such as the collapse of quicksand.

An interesting experiment that has been devised by Ranjini's group during 2014-2015 has been that of a falling ball on aging Laponite colloidal suspensions. The falling of an object through a non-Newtonian aging suspension leads to a very interesting scenario as one can observe manifestations of Stokesian flows without any terminal velocity. Samim Ali, Debasish Saha and Ranjini have performed falling ball experiments in aging colloidal suspensions of Laponite. Balls of different sizes are dropped through the suspensions with different initial states of structure. The velocity of the ball as it gets deeper into the fluid is observed to increase. This increment is most pronounced for the largest ball and for lower aging or waiting times of the suspensions. A simple rheological model is constructed by taking into account

(i) Restructuring and de-structuring processes and
(ii) The dependence of the viscosity of the suspensions on structure parameter and shear rate, to explain the experimental results.

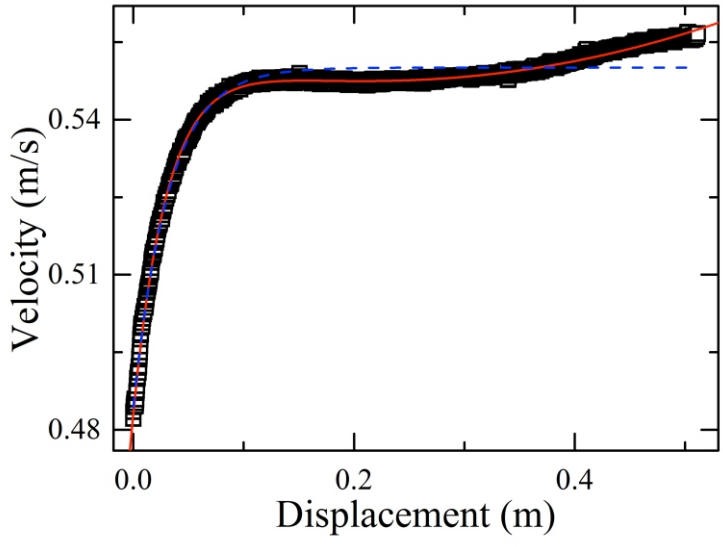


Fig. 3: Velocity of a steel ball of 4 mm in diameter falling through a Laponite suspension of 3.5% (w/v) of waiting time t_w = 30 minutes plotted as a function of the displacement from the free surface of the tube. The solid line with red in colour and the dashed line with blue in colour are fit to equation (1) and (3) respectively.



Fig.4: Falling Ball Viscometer

So far as usage of of major RRI instruments goes, Ranjini and her group have used the scanning electron microscope in the cryogenic mode extensively for the following studies:

1) To look at hydrogel morphology (Soft Matter, **10** (37), 72257233, 2014).
2) To look at Laponite and Na-montmorillonite clay gels (To be published).

Yashodhan Hatwalne's areas of research interests include phenomenological theories of liquid crystals, membranes and polymer crystallization. During the past year, his research has essentially followed four themes.

With Jaya Kumar A. (PhD student, RRI) and M. Muthukumar (University of Massachusetts, Amherst) he has worked on the morphology of polymer crystallites. Polymer crystallites exhibit diverse morphologies. Melt-grown crystallites of achiral polymers such as polyethylene have spherulitic structure made up of helicoidal lamellae that break chiral symmetry. Y. Hatwalne and M. Muthukumar gave a phenomenological theory for this. (Phys. Rev. Lett. 105, 107801 (2010)). Apart from this morphology, polymer crystallites grow in the form of tents, chairs, and scrolls. The stability of these structures has not been understood, and no unified theoretical framework explaining all observed morphologies exists. This has been a long-standing problem in polymer physics (see, for example, B. Lotz and S. Cheng, Polymer 46, 577 (2005)) and references therein).

His second theme of research (with Jaya Kumar A. (RRI) and Buddhapriya Chakrabarti (University of Durham, UK)) has been on the equilibrium of fluid membranes having tangent-plane order (such as nematic-, vector-, and hexatic orders). Tangent-plane order (TPO) on two-dimensional membranes deformable in three dimensions leads to frustration of the TPO on curved membranes. Nelson and Peliti (J. Physique 48, 1085 (1987)) formulated the covariant elasticity theory of such membranes (the "spin-connection" formalism). Using this formalism, Hatwalne and collaborators have obtained the equations of equilibrium together with free boundary conditions. Extending the spin connection formalism to thermotropic and lyotropic smectic liquid crystals with TPO, they have shown that for chiral smectic-C* this

generalisation leads to experimentally verifiable consequences for dispirations having topological indices of the same magnitude but opposite signs.

With Jaya Kumar A. (RRI), Hatwalne has worked on the structural classification of graphene nanotori.

His fourth research theme over the past year has been the study of topological instabilities in lyotropic smectic-A liquid crystals (in collaboration with Jaya Kumar A. (IISc), and Rahul Pandit (IISc)).

Sandeep Kumar's research interests primarily focus on liquid crystal nanoscience and synthesis and physical studies of liquid crystals.

Under the first theme of Liquid Crystal Nanoscience, Kumar has embarked upon the following projects during the period 2014-2015 which are described below-

(i) Luminescent CdTe quantum dots incarcerated in a columnar matrix of discotic liquid crystals for optoelectronic applications. Collaborating with Manish Kumar, he has demonstrated, for the first time, the effects of highly luminescent alkylamine-capped semiconductor cadmium telluride quantum dot (CdTe QD) dispersion on the optical, electrical, and thermal properties and supramolecular order of a discotic liquid crystal (DLC). The insertion and properties of CdTe quantum dots in the columnar mesophase were studied by UV-vis spectroscopy, photo luminescence spectroscopy, polarized optical microscopy, differential scanning calorimetry, X-ray diffraction and DC conductivity. Results indicated a uniform dispersion of CdTe QDs in a columnar matrix without disrupting the mesophase but enhancing the conductivity of the system significantly.

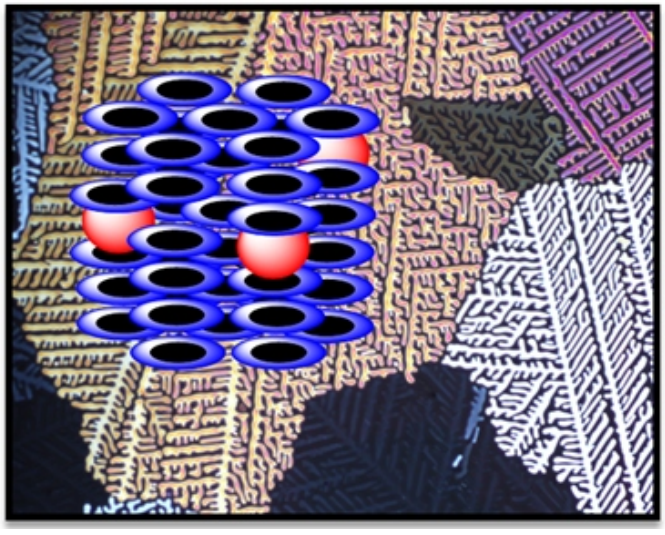


Fig.1 (Image credit: Manish Kumar and Sandeep Kumar,(2015): "Graphical Abstract", Luminescent CdTe quantum dots incarcerated in a columnar matrix of discotic liquid crystals for optoelectronic applications, RSC Adv., 5, 1262.)

(ii) Stacking of ultra-thin reduced graphene oxide nanoparticles in supramolecular structures for optoelectronic applications with Manish Kumar. Octadecylamine functionalized ultra-thin reduced graphene oxide nanoparticles were synthesized and dispersed in the supramolecular order of discotic liquid crystals for the first time. The

insertion and properties of the graphene nanoparticles in the columnar mesophase were studied using field emission scanning electron microscopy, atomic force microscopy, Raman spectroscopy, UV-vis spectroscopy, photo luminescence spectroscopy, polarized optical microscopy, differential scanning calorimetry, X-ray diffraction and DC conductivity. Experimental studies indicate the stacking of two-dimensional graphene nanoparticles in the supramolecular order of the columnar mesophase. The dispersion of graphene nanoparticles improves the order in the columnar phase and thus enhances the conductivity of the system.

(iii) Ultrathin films of TiO2 nanoparticles at interfaces along with R. K. Gupta. The properties of a material change remarkably as a result of the scaling dimensions. The Langmuir-Blodgett (LB) film deposition technique is known to offer precise control over the film thickness and the interparticle separation. To form a well-ordered LB film, it is essential to form a stable Langmuir film at the air-water interface. In this work they report their studies on ultrathin films of TiO_2 nanoparticles at air-water and air-solid interfaces. The Langmuir film of TiO_2 nanoparticles at the air-water interface was found to be very stable, and it exhibits loose-packing and close-packing phases. The LB films were transferred onto solid substrates for characterization and application. The surface morphology of the LB film was obtained by a field emission scanning electron microscope. The optical and electronic properties of the LB films of TiO_2 nanoparticles were studied using UV-vis spectroscopy and current-voltage measurements, respectively. The LB film of TiO_2 nanoparticles was employed for ethanol gas sensing, and the sensing performance was compared to that of bulk material. Because of the enormous gain in the surface to volume ratio and the increase in crystalline defect density in the ultrathin LB film of TiO_2 nanoparticles, the LB film is found to be a potential functional layer for ethanol sensing as compared to the bulk material.

(iv) Effects of copper nanoparticles on the thermodynamic, electrical and optical properties of a disc-shaped liquid crystalline material showing columnar phase in collaboration with R. Dhar. Thermodynamic, electrical and optical studies have been carried out on a discotic liquid crystal (DLC), namely 2, 3, 6, 7, 10, 11-hexabutyloxytriphenylene (possessing columnar phase) and its copper nanoparticles (0.6 wt%) based composite. The ionic conductivity of DLC-copper nanocomposite has increased by about two orders of magnitude as compared to the pure system. Dielectric permittivity has also increased. The absorption spectra for pure and nano composites have been studied by UV-vis spectrophotometer. The optical study suggests that surface plasmon resonance has been introduced in DLC due to the incorporation of copper nanoparticles. It has been observed that the presence of nanoparticles has decreased the optical band gap to 3.3 eV from 4.2 eV of the pure DLC. Enhanced properties are useful for one-dimensional conduction and photovoltaic applications.

(v) Effect of the dispersed colloidal gold nano particles on the electrical properties of a columnar discotic liquid crystal in conjunction with R. Dhar. A dispersion of colloidal gold nanoparticles (GNPs) in a triphenylene-based discotic liquid crystal (DLC), namely 2,3,6,7,10,11-hexabutyloxytriphenylene (HAT4), possessing a hexatic plastic columnar phase (Col_{hp}) phase, has been studied by differential scanning calorimetry, polarized light microscopy, UV-vis absorption spectroscopy, X-ray diffraction and dielectric spectroscopy. GNPs have been dispersed at three different concentrations in pure HAT4 viz. 0.2, 0.6 and

1.2 wt%. It has been observed that with the increase of GNPs concentration, the Col_{hp}–isotropic liquid transition temperature decreases substantially but the crystal–Col_{hp} transition temperature does not change significantly. Electrical conductivity increases by at least five orders of magnitude for the highest concentration of GNPs (1.2 wt%) as compared to the pure material i.e. HAT4. Observed results suggest that although extremely low concentrations of GNPs are not very useful, a moderate concentration is highly useful for increasing the conductivity of the Col_{hp} phase and also to implant surface plasmon resonance. These results may be exploited to enhance the efficiency of electro-optical devices by using HAT4–GNPs composites.

(vi) Electro-optical and Dielectric Properties of CdSe Quantum Dots and 6CHBT Liquid Crystals Composites with R. Dhar, They have prepared the composites of a room temperature nematic liquid crystal namely 4-(trans-4-n-hexylcyclohexyl) isothiocyanatobenzoate (6CHBT) and Cadmium Selenide Quantum Dots (CdSe-QDs) and investigated their electro-optical and dielectric properties. Effect of dispersion of CdSe-QDs on various electro-optical and display parameters of host liquid crystalline material have been studied. Physical parameters, such as switching threshold voltage and splay elastic constant have been altered drastically for composites. Dispersion of QDs in a liquid crystals medium destabilizes nematic ordering of the host and decreases the nematic-to-isotropic transition temperature.

(vii) Effect of octadecylamine functionalized SWCNTs on the elastic constants and electro-optic response of a liquid crystal with R. K. Gupta. By suitably altering the physical properties of the LC materials through incorporating nano materials like carbon nanotubes (CNTs), graphene and quantum dots, more efficient and high-performance liquid crystal (LC) devices may be designed. In the present work, the effect of incorporation of octadecylamine-functionalised single-walled carbon nanotubes (ODA-SWCNT) in a LC exhibiting nematic and smectic phases on its physical properties is investigated. 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 decreased and decay time increased at higher concentrations of ODA-SWCNT. The temperature range of smectic phase is increased with an increase in the concentration of ODA-SWCNT. 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.

(viii) Electro-Optic and Dielectric Studies on Quantum Dot doped Nematic Liquid Crystal with R. K. Gupta. Liquid crystals are shape anisotropic organic materials which find many applications in a wide variety of fields such as display technology, bioscience and surface science. On doping the liquid crystals with nano materials such as nanoparticles or carbon nanotubes the switching properties can be altered. In this report, the electro-optic and dielectric properties of cadmium selenide quantum dots (CdSe QDs) doped nematic liquid crystal (NLC) is presented. The nematic liquid crystal was doped with different concentrations of the semiconducting QDs. The nematic to isotropic (N-I) transition temperature for doped sample is comparable

to that of pure NLC. The doped sample is found to have a lower threshold voltage than that of pure NLC. The value of threshold voltage decreases with increasing concentration of the QDs. The dielectric permityivity is estimated as a function of temperature in both planar and homeotropic geometry. Doping QDs led to increase in dielectric anisotropy in comparison with that of pure liquid crystal. The result showed that the incorporation of QDs into NLC provides a way to improve the performance of LC based devices.

(xi) Reduced ionic contaminations in CdSe quantum dot dispersed ferroelectric liquid crystal and its applications with Rajiv Manohar. Octadecylamine capped cadmium selenide quantum dots (CdSe QDs) were dispersed in the ferroelectric liquid crystal (FLC) FELIX 16/100. The QD dispersed FLC system was investigated on the planar anchored cell. Addition of specific concentration of the QDs in the pure FLC induces a new relaxation mode along with the Goldstone relaxation mode. QDs assisted quantum fluctuations are probably responsible for the existence of this new relaxation mode in the QDs dispersed FLC system. The ionic contaminations associated with the FLC materials were trapped on the surface of QDs due to the ion-trapping character of QDs. The trapping of ionic contaminations was confirmed by the a.c. conductivity measurement. The physical properties of the pure and dispersed FLC were carried out as a function of doping concentration of QDs, temperature and frequency.

(x) Effect of cadmium selenide quantum dots on the dielectric and physical parameters of ferroelectric liquid crystal with Rajiv Manohar. In this work, the effect of cadmium selenide quantum dots (CdSe QDs) on the dielectric relaxation and material constants of a ferroelectric liquid crystal (FLC) has been investigated. Along with the characteristic Goldstone mode, a new relaxation mode has been induced in the FLC material due to the presence of CdSe QDs. This new relaxation mode is strongly dependent on the concentration of CdSe QDs but is found to be independent of the external bias voltage and temperature. The material constants have also been modified remarkably due to the presence of CdSe QDs. The appearance of this new relaxation phenomenon has been attributed to the concentration dependent interaction between CdSe QDs and FLC molecules.

Under Kumar's second research theme of design, synthesis and physical studies of liquid crystalline materials, his research during the previous year consisted of the following projects -

(I) Synthesis, characterization and nonlinear optical studies of novel blue-light emitting room temperature truxene discotic liquid crystals with Reji Philip. A new series of discotic liquid crystals based on a truxene core has been synthesized to study the structure–property relationship in view of the self-assembling property and their linear and nonlinear optical properties. All these branched alkyl chain truxene derivatives show the mesogenic property in a columnar hexagonal fashion at room temperature, which is studied by a combination of different techniques. The newly synthesized truxene discotic 7a possesses a clearing temperature of 117°C, one of the lowest clearing temperatures known in truxene discotic liquid crystals. We have discovered that the introduction of branching near to the core even in a small alkyl chain drastically reduces the isotropic temperature. Due to their C3 symmetry and their large first hyperpolarizability, these truxene derivatives show long-lived emissions in the solution state at room temperature. The group also reports a large effective three-photon

absorption in these materials under nanosecond laser pulse excitation at 532 nm, which makes them suitable candidates for optical limiting applications.

(ii) Synthesis and Characterization of Novel Azobenzene-based Mesogens and their organization at Air-water and Air-solid Interfaces with S.K. Pal. Eight new oligomeric mesogens are reported, consisting of an azobenzene-based core attached to which are four 4-cyanobiphenyl units via flexible alkyl spacers (n = 5–12). 1H NMR, 13C NMR, IR, UV-Vis and Raman spectroscopy, and elemental analysis determined their chemical structures. POM, DSC and XRD experiments were employed to investigate the thermo tropic liquid crystalline properties of these materials. The oligomers containing n = 8 and n = 10 were found to exhibit a monotropic nematic (N) phase while others were non-mesomorphic. Langmuir monolayers and Langmuir–Blodgett films of the nematic compounds (n = 10) were studied at the air–water interface (Langmuir film) and the air–solid interface. Surface manometry studies on the Langmuir monolayer showed that the film had nearly zero surface pressure at a large area per molecule (Am $\geq$ 0.55 nm^2). The film on compression showed a gradual increase in surface pressure and finally collapsed at an Am of about 0.15 nm^2 with a collapse pressure of about 60mN m-1. Brewster angle microscopy (BAM) images (during compression) showed that dark regions coexisting with grey spots in large areas transformed to a uniform grey region with an increase in surface density and finally collapsed exhibiting bright regions. Atomic force microscopy studies (AFM) on the LB films, transferred onto freshly cleaved hydrophilic mica substrates, exhibited a network of thin fibers with the height of fibers varying between ~4 nm to 80 nm which could be due to p–p stacking and dipolar interactions associated with the cyanobiphenyl units. On a hydrophobic silicon substrate, the LB transfer yielded a multilayer film, which dewetted to form nano droplets. We carried out temperature dependent AFM studies of the nematic compounds, which showed the reversible formation of aligned fibers (~20 to 40 mm) in the mesophase. In brief, our study provides new approaches for the realization of controlling the anisotropic properties of an ordered phase.

(iii) Synthesis and photo switching properties of liquid crystals derived from myo-inositol in conjunction with Md Lutfor Rahman. A new series of unconventional liquid crystal molecules derived from myo-inositol core were synthesized by linking six azobenzene units having terminal double bonds as polymerizable functional groups to myoinositol. Differential scanning calorimetry, polarizing optical microscopy and X-ray diffraction studies were carried out to determine mesomorphism in these materials. All compounds showed stable enantiotropic SmA phase independent of the chain length and chain parity. The photo switching behaviour of these molecules in solutions showed E to Z isomerization in 8–10 s, whereas the reverse process took about 270–305 min. In solid film, the E–Z photoisomerization took 5 s, while the reverse transformation from Z to E state took 120 min. The photo switching behaviour of these materials represents one of the fastest switching times so far observed in such materials and, therefore, they are good candidates for molecular switches.

(iv) Pattern formation in Langmuir-Blodgett flms of tricycloquinazoline based discotic liquid crystal molecules with R. K. Gupta. The assembly of molecules on the surface has drawn considerable attention because of its potential to tailor the physicochemical, electronic, and magnetic properties of materials. The structure of aggregates of molecules can be influenced by the molecular interactions and the external parameters like

temperature, pressure and ion contents. They have found a stable Langmuir monolayer of amphiphilic tricycloquinazoline based discotic liquid crystal (AmTCQ) molecules at air–water (A–W) interface. The monolayer exhibits gas phase, low density liquid phase and high density liquid phase. The structural evolution in Langmuir–Blodgett (LB) films of the AmTCQ molecules as a function of target surface pressure is studied using an atomic force microscope. Aggregations of the discotic molecules were found, leading to nucleation sites at a lower surface pressure. With the increasing surface pressure, each nucleation site grows to form a stable triangular structure. The shape and size of the triangular structure remain stable till the target surface pressure for LB films deposition exceeds the equilibrium surface pressure of the AmTCQ molecules. The number of triangles in the film increases with increasing target surface pressure of LB deposition. The target surface pressure of LB deposition acts as a controlling parameter for obtaining desired number of triangular domains in the film.

(v) Synthesis and characterization of naphthalene-based banana-shaped liquid crystals for photo switching properties with Md Lutfor Rahman. A series of banana-shaped monomers containing naphthalene as central unit, azobenzene in side arms with terminal alkenes were synthesized and characterized. Polarizing optical microscopy, DSC and X-ray diffraction measurements reveal that one compound processes a nematic phase while other four compounds exhibit B6 phase. The absorption spectrum of *trans*-azobenzene displays high-intensity π-π^* transition at 365 and low-intensity n-π^* transition at 450 nm. These molecules exhibit strong photoisomerisation behaviour in solutions in which *trans* to *cis* isomerisation takes 55 seconds whereas reverse process takes about 32 hours. Such a long thermal back relaxation is useful for creation of optical image storage devices.

(vi) Orientational order parameter measurements of discotic liquid crystal with R. Pratibha and K.K. Raina. The IR dichroism technique is a convenient method, which can be used to measure the molecular order parameter corresponding to the IR bands exclusively present in the disc –like molecules in discotic liquid crystal (DLC). To measure orientational order parameter, homeotropic alignment of discotic liquid crystal was attained by slow cooling of sample from isotropic phase on untreated flat CaF_2 substrate. The homeotropic alignment thus achieved was found to be thermodynamically stable in the discotic mesophase. IR spectra were recorded at different temperatures for the DLC. The order parameter was calculated by comparing the spectra of discotic phase with that of the isotropic phase. Order parameter has been presented as function of temperature for different significant IR bands present in the DLC.

(vii) Formation of H-type liquid crystal dimer at air-water interface with R. K. Gupta. They have formed the Langmuir monolayer of H-shaped Azo linked liquid crystal dimer molecule at the airwater interface. Isocycles of the molecule showed hysteresis suggesting the irreversible nature of the monolayer formed. The thin film deposited on the silicon wafer was characterized using Atomic Force Microscopy (AFM) and Field Emission Scanning Electron Microscopy (FESEM). The images showed uniform domains of the dimer molecule. They propose that these molecules tend to take bookshelf configuration in the liquid phase.

Pramod Pullarkat's areas of current professional research interests are in studying shape instabilities in axons leading to axonal atrophy, mechanical properties of axons and pattern formation in differentiating stem cells. Axons are thin tubular extensions

produced by neuronal cells in order to conduct electrical signals.

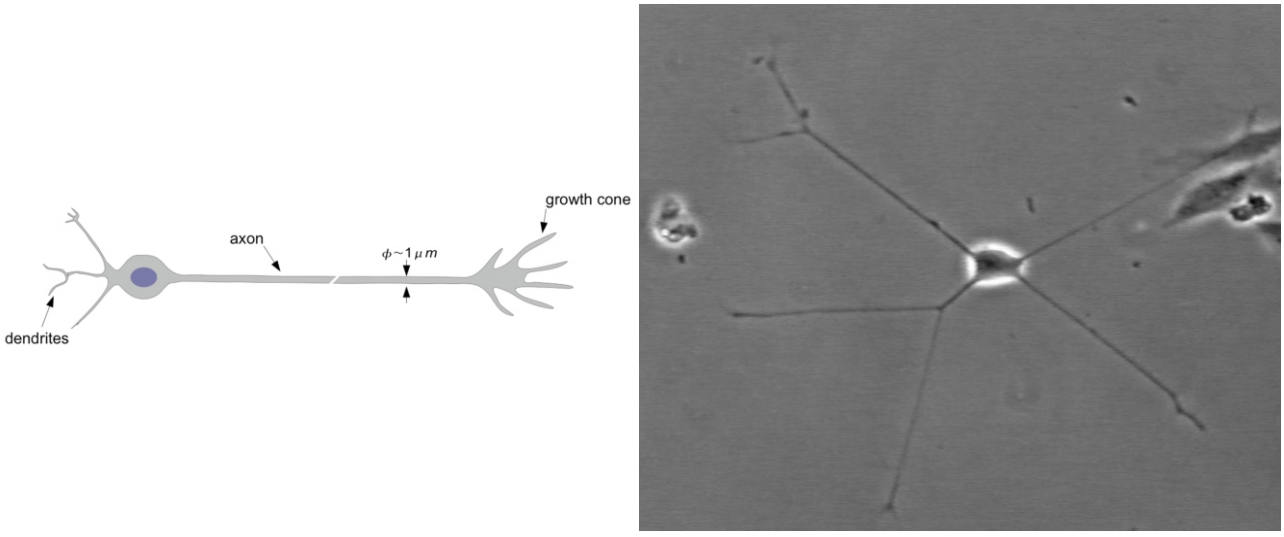


Fig.1: A schematic drawing of a neuronal cell and a microphotograph of a cell grown in the lab.

Axons are aplenty 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 an 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). Maintenance of a uniform diameter is essential for signal transmission. Moreover, retaining axonal plasticity requires that the neuronal cell should be able to extend and retract connections. Here it is suspected that molecular motors are at work as they can generate active stresses. The questions that are of interest in this context are: How do axons maintain this 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? What drives axonal atrophy resulting from neurode generative conditions?

The group at RRI approaches the problem mainly by developing biochemical assays, image analysis techniques, and confocal fluorescence microscopy. It also uses the optical tweezers method to measure the mechanical properties of the cell membrane. Probing the retraction and stress relaxation response of axons to laser induced ablation is another technique that is employed.

Using these techniques, group members Anagha Datar, Roli Srivastava and Alka Bhat have shown that axonal loss resulting from induced degeneration occurs via two distinct modes:

(i) A peristaltic mode that travels and coarsens with time resulting in axonal atrophy and
(ii) A retraction mode characterized by a single travelling front.

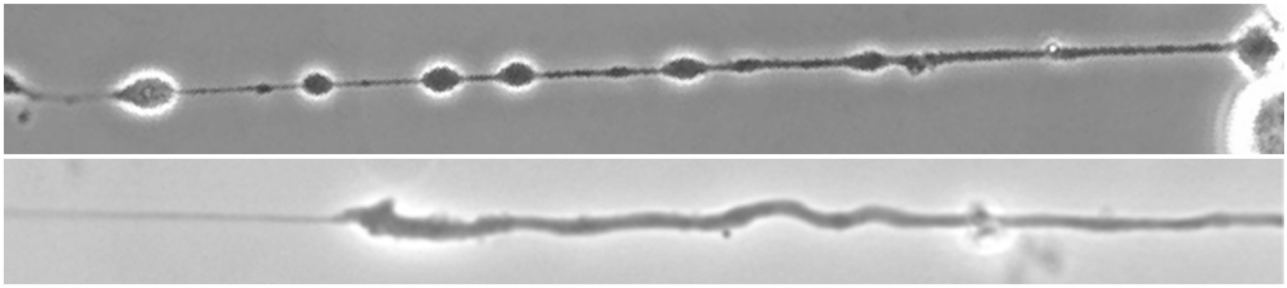


Fig.2: Two distinct modes of axonal atrophy resulting from biochemically induced degeneration. The internal cell matrix flows from the tip (left side) to the cell body (right side) causing neuronal disfunction.

The group has shown that these shape instabilities are driven by the combined physical effects of cell membrane elasticity and stresses built into the internal cell cytoskeleton—a complex, dynamic, biopolymer network which renders mechanical stability to the cell. It has also disproved earlier suggestions by other researchers that hindrance of axonal transport is the primary cause for the shape transformations. Theoretical analysis of this process is being carried out with Prof. Jacques Prost, Institut Curie, Paris. It is expected that further detailed investigation of this process will lead to a better understanding of neurodegeneration mechanism and possible strategies for preventing axonal loss.

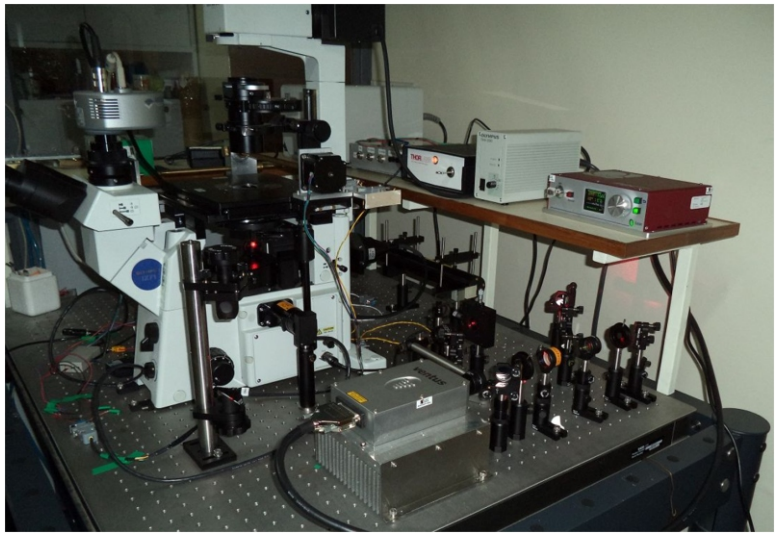


Fig.3: Measuring force using light: the optical trap setup built in-house uses a focused laser beam to trap micron sized dielectric beads in the optical field. The force exerted by the cell membrane on the attached bead is used to extract the membrane mechanical response with picoNewton sensitivity.

Maintenance of axonal plasticity (growth and retraction) and the ability to span long distances require unique mechanical properties. Together with past members (Seshagiri Rao and Chirag Kalelkar) the laboratory has designed and built an optical fibre based force apparatus with pico-Newton sensitivity, nano-meter position resolution and feedback control. This force apparatus uses a cantilever consisting of a uniformly etched optical fibre attached to a computer controlled piezo drive to apply or measure

forces. Changes in the internal organization of the axon can be imaged fluorescence microscopy simultaneous with force measurement. A feedback loop allows for independent control of the force or extension. During the previous year, in collaboration with Sushil Dubey (PhD student, RRI), Aurnab Ghose (IISER, Pune) and Andrew Callan-Jones (University-Paris, Diderot), the group has performed rheological measurements on axons using the constant-strain mode that was implemented into the force device. The data shows that detachment dynamics of protein crosslinks is central to the dissipative behaviour (viscoelasticity) in axons.

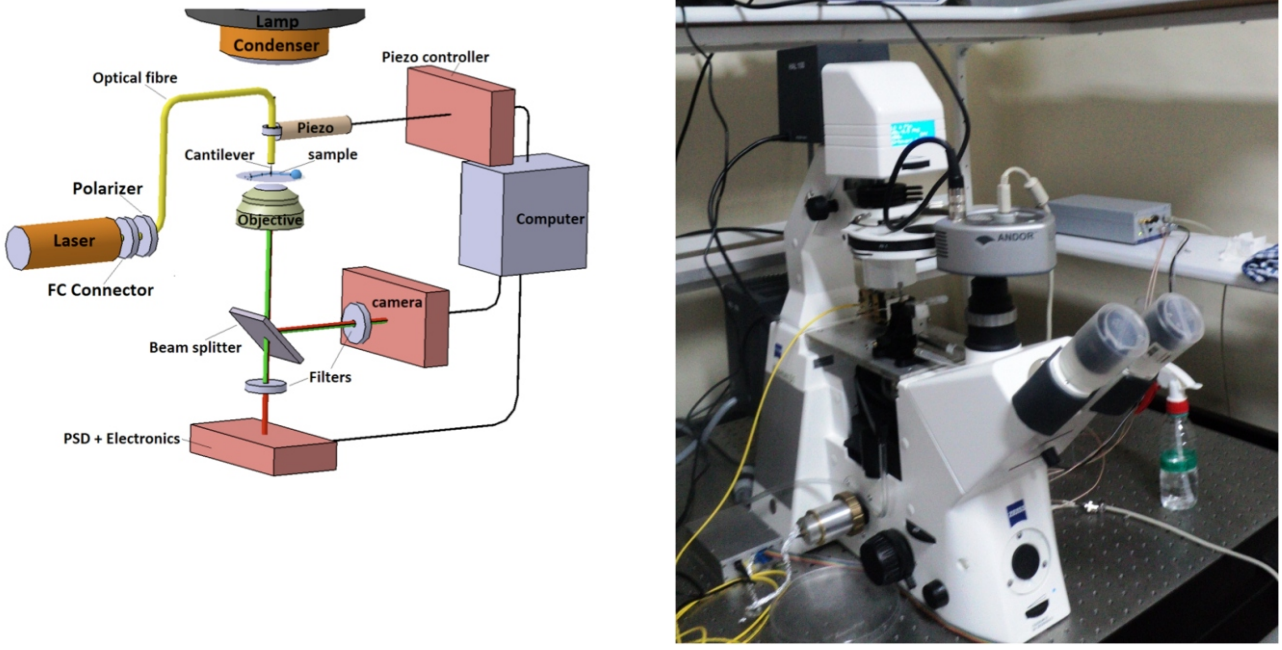


Fig.4: The schematic and photograph of the optical fiber force apparatus designed and built at RRI to investigate mechanical responses (rheology) of axons (Patented).

The labs project on differentiating stem cells was started with the aim of understanding the role of physical forces in regulating cell geometry and cell-substrate interaction. Along with Renu Vishavkarma, Pramod has shown that actin cables running over the cell nucleus plays an important role in dictating cell shape and can explain the changes in cell shape as a function of substrate properties like stiffness or adhesivity. Renu has also developed a shear device for studying the effect of shear stress on cells along with fluorescence microscopy. She 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.

The group also studies cell membrane physics using the optical tweezers method. A collaborative work with French scientists has shown that cell membranes pulled out of cells using tweezers exhibit a non-exponential force relaxation behaviour which can be explained by a simple model invoking hindered diffusion. Active contractile responses of membranes have also been studied and is a topic of current research

using the optical tweezers developed at RRI by Susav Pradan, a problem that has not yet been fully understood. In collaboration with the lab of Prof. Satyajit Mayor at NCBS and his student Joseph Thottacherry, Renu has also studied the effect of cell spreading on membrane tension using chemically micro-patterned surfaces.

Pratibha R. is primarily interested in chirality in liquid crystals, electric field induced phase transitions in liquid crystals, dielectric properties of poly electrolytes and liquid crystal-nano particle composites. During the past year, her work has centred around a number of broad themes such as

i) The influence of layer deformation and chiral segregation on dielectric modes in the dark conglomerate liquid crystal,
ii) Low frequency dielectric dispersion in polyelectrolytes,
iii) Transition between two lamellar SmCP phases both with antiferroelectric order in a bent-core liquid crystal and
iv) Stabilization of polar order under applied electric fields in bent-core liquid crystals.

i) Bent-core liquid crystals (BCLCs) are a unique class of materials in which chirality is generated by achiral molecules. The presence of polar order, ability to form chiral superstructures, high values of spontaneous polarization and potential to exhibit electro-optic switching, makes these liquid crystals ideal candidates for electro-optic and NLO applications. BCLCs exhibit both lamellar and columnar phases, among which the lamellar dark conglomerate (DC) phase characterized by macroscopic chiral symmetry breaking, are the most interesting. The optical texture in this phase is totally dark when observed between crossed polarizers and domains of opposite chirality, which appear alternately dark and bright, are revealed only on rotation of the analyzer by a few degrees. It has been proposed that this phase is macroscopically isotropic and that layer frustration is relieved by saddle splay layer deformation. The spontaneous formation of homogeneous dark or bright domains in the DC phase eliminates the difficult task of forming mono-domain aligned regions, which is an essential prerequisite for display applications. Control of the size and chiral sense of the domains in the DC phase can lead to novel chiro-optical effects. However most often the DC phase does not respond to external fields. Along with G.B. Deepa (PhD student, RRI), Pratibha has recently succeeded in obtaining switchable DC phases in the BCLC, 2,7-naphthylene bis[4-(3-methyl-4-*n*-tetradecyloxybenzoyloxy)] benzoate which normally exhibits two types of reverse columnar phases viz. B_{1rev} and $B_{1revtiltM}$, in both of which, the density modulation is present in the plane perpendicular to the polarization vector. The DC phases were formed by two methods

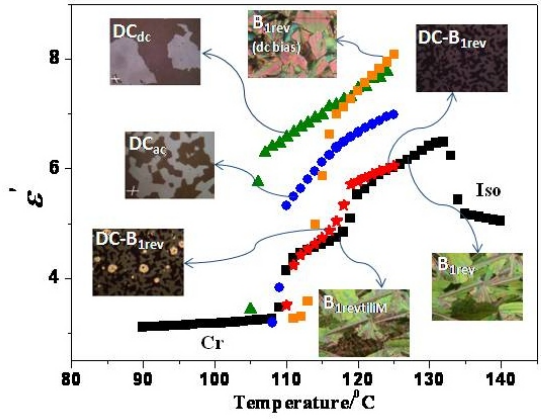
(a) Application of a high frequency ac electric field in the B_{1rev} phase resulting in the DC-B1revphase or
(b) Cooling from the isotropic phase under a dc or ac field forming the DC_{dc} or DC_{ac} phases respectively.

Moreover, they have also demonstrated that enantioselectivity and switching polarization in these field induced DC phases can be varied. In order to further characterize the switchable DC phases and have a better control on the electro-optic responses for integrating in practical devices, it is essential to understand the structural details, the extent of chiral segregation and molecular motions in the different types of DC phases.

Dielectric spectroscopy is a versatile technique used to gain information on structure and molecular dynamics in BCLCs where the special types of packing of polar molecules in different phases influences the dielectric spectrum, giving information about

molecular reorientations and dynamics of polar super structures and also reveals how some of the motions may be hindered. Although dielectric behaviour has been investigated in many of the lamellar phases exhibited by BCLCs, detailed studies in the DC phase have not been reported. Pratibha undertook both static and frequency dependent dielectric studies in order to probe the differences between the various DC phases, which could aid in tuning the switching properties. The results were also compared with the dielectric behaviour in the columnar B_{1rev} and $B_{1revtiltM}$ phases formed in the same compound before application of the electric field. The dielectric behaviour in the $B_{1revtiltM}$ phase is consistent with the modulated layer structure that this group had proposed earlier for this phase based on x-ray diffraction studies, which further confirms that this is a novel type of reverse columnar phase that had not been observed earlier.

The studies in the field induced DC phases show that in spite of the electro-optic responses being similar to that observed in typical SmCP phases with flat layer structures, the dielectric relaxation modes are damped and comparable to that observed in reverse columnar phases or in the non-switchable DC phase formed by a lower homologue of the same series. It is therefore proposed that molecular reorientations are hampered because of layer deformation, resulting in a lowering of the static permittivity and dielectric strength, whereas collective fluctuations of polar domains become more prominent. They also find that the conformational chirality of the bent-core molecules and the morphology of nucleating domains under the field affect the chiral segregation, which in turn influences the dielectric properties.



Temperature variation of real part of permittivity in the reverse columnar and field induced DC phases

Fig.1: Temperature variation of real part of permittivity in the reverse columnar and field induced DC phases [Image credit: Deepa GB.Radhika S, Sadashiva BK and Pratibha R (2015):Possible influence of layer deformation and chiral segregation on dielectric modes in the dark conglomerate liquid crystal, ChemPhysChem, 16,825]

ii) Polyelectrolytes have the potential to be used in a variety of applications ranging from functional colloids to bio-compatible devices. Understanding the properties and formation of complexes of polylectrolytes is a very active and ongoing field of research. The dielectric properties of aqueous polyelectrolytes differ considerably from that of neutral macromolecules or low molar mass electrolytes. The dielectric response shows

distinct relaxations both in the high and low frequency regimes. The high frequency relaxation occurring in the GHz region corresponds to the orientational polarization of water molecules whereas low frequency relaxations owe their origin to counterions. They can be related with the charge distribution along the polyelectrolyte chain, which is dictated by the condensation of the counterions. This can also aid in distinguishing between two types of counterions, those that stay close to the charged polymer and the free counterions that dissociate from the polymer chains.

Pratibha along with Pramod Tadapatri (RRI) and M. Muthukumar (University of Massachusetts) have been carrying out dielectric studies on the polyelectrolytes viz. Poly(allylamine hydrochloride) (PAH) and Poly(acrylic acid) (PAA) and related coacervates and find some evidence for relaxation process at extremely low frequencies. However in the very low frequency regime the dielectric parameters of aqueous polyelectrolytes can be severely affected by high ionic conductivity of water, which makes it difficult to distinguish contributions to the dielectric spectrum from the polymers. The other hampering factor is the strong electrode polarization. Therefore it is experimentally very difficult to probe the low frequency regime of the dielectric spectrum of polyelectrolytes. Currently they are in the process of carrying out more detailed measurements of the conductivity, dielectric increment and relaxation time in order to characterize the slow relaxation processes. The effect of solute concentration, pH and temperature is also being looked into. They have also undertaken dielectric dispersion studies on synthetic single stranded DNA, as the length and degree of polymerization are well defined in this case and ambiguities associated with length distributions can be overcome.

iii) Polar phases exhibited by bent-core liquid crystals (BCLCs) are interesting from both fundamental and technological points of view and hence several strategies are adopted to design compounds that exhibit interesting phase sequences. Factors like intermolecular interactions, conformation chirality, steric effects and polar order are responsible for the formation and stabilization of various lamellar and columnar mesophases formed by BC molecules. Introduction of substituents either in the central core or in the arms of the bent-core molecule can significantly alter the nature of the mesophase. In the lamellar SmCP phase, polar ordering in each layer and molecular tilt about the arrow axis results in layer chirality. The interlayer ordering can be ferro or antiferroelectric and the orientation of the molecules can be either synclinic or anticlinic between the adjacent layers. Variants of the SmCP phase are designated by the general formula $SmC_{S,A}P_{F,A}$ where the subscripts S and A of C stand for synclinic and anticlinic orientations and subscripts F and A of P for ferroelectric and antiferroelectric forms. In the SmC_SP_A and SmC_AP_F types the layer chirality alternates from layer to layer and the structure is racemic, whereas in the SmC_AP_A and SmC_SP_F types the structure is homochiral. In collaboration with S. Radhika (RRI) and B.K. Sadashiva (RRI) Pratibha has recently investigated the mesomorphic properties of two homologous series of BC compounds derived from 2,7-dihydroxynaphthalene in which the influence of electron withdrawing and electron donating lateral substituents have been examined. These studies clearly show that dipolar effects are significant. The two series differ from one another by an electron withdrawing or an electron donating lateral substituents on the middle phenyl ring of the arms of the bent-core. Contrasting results are obtained in which polar phases are observed in compounds containing a chloro substituents and a polar smectic C and nematic phases are obtained when a methyl

group replaces this substituents. The mesophases have been characterised by using a combination of polarised light optical microscopy, differential scanning calorimetry, X-ray diffraction measurements, electro-optical and dielectric studies.

Interestingly in the series with the chloro substituents, when the alkyl chain length η=16 or 18, a phase transition between two lamellar polar phases both having synclinic tilt and antiferroelectric order can be observed in addition to a nematic phase. The SmCP phases have therefore been named as SmC_SP_A and SmC_SP_A. Phase transitions between two such antiferroelectric phases are quite rare. In order to distinguish between the two phases having very similar phase structures, measurements of the temperature and frequency dependent dielectric parameters were undertaken. The static permittivity (ε) measured at a frequency of 10 kHz initially revealed a sharp increase at the transition from the N to SmC_SP_A phase that could be due to the increase in the positive dipole correlation in the lamellar phase. With further decrease in temperature, the transition into the SmC_SP_A phase was marked by a pronounced reduction in ε which can be ascribed to a reduction in the dipole-dipole correlation at lower temperatures, without there being any drastic changes in the overall structure. Changes in molecular conformation or tilt angle with decrease in temperature can contribute to a partial compensation of the dipole moments. In fact, x-ray diffraction studies show that the layer spacing increases in the SmC_SP_A phase, indicating that there is a decrease in tilt angle. The frequency response shows up a single mode present in the kHz region with the relaxation frequency being much lower than what is normally observed for the mode related with molecular reorientation around the long-axis. This is due to the more pronounced hindered rotation caused by Cl at the *meta* position. As the molecule is symmetric, rotation around the short axis can be ruled out An analysis of the dielectric response using the Cole-Cole procedure shows that the dielectric strength increases initially in the SmC_SP_A phase, attains a maximum and later starts decreasing as the temperature of the sample is lowered. This again confirms that there is a reduction in the dipole correlation leading to a transition between the two antiferroelectric phases.

iv) The lamellar SmCP phases formed by bent-core molecules usually consist of a well-established polar order within the layers. Generally the spontaneous electric polarization is compensated by an antiferroelectric arrangement of molecules in the adjacent layers. Another way in which bulk spontaneous polarization can be avoided is by forming 2D periodic structures in which the layers are broken. This leads to fragmented ribbons or domains of the smectic layers that organize such that the bend directions of the molecules in adjacent ribbons are antiparallel, resulting in an escape from macroscopic polarization. Among these, the B_1 phase in which the density modulation is in the plane parallel to the polarization vector is the most widely observed columnar phase exhibited by bent-core molecules. This phase does not respond to electric fields as steric hindrance caused by interactions between column boundaries limits molecular rotation. The density modulation can also be present in the plane perpendicular to the polarization vector as in the reverse columnar B_{1rev} and $B_{1revtilt}$ phases. Switching under the field does not require breaking of the columnar structure in these phases. Thus they are electrically switchable and have polar and optical properties distinctly different from the B_1 phase. Usually in BCLCs either the lamellar or columnar phase is present in the same compound and phase transitions between the two are extremely rare because of the difficult structural rearrangements that are required. However under the influence of high

electric fields, the polar order within the layers can be expected to be enhanced, leading to a destabilisation of the columnar structure and resulting in the formation of smectic lamellar phases. However there are very few reports of such phase transitions.

In order to investigate these types of phase transitions and study the effect of electric field on polar order, Pratibha R. and Pramod Tadapatri (RRI) are presently investigating a special BCLC derived from 5-methoxyisophthalic acid which exhibits a phase transition between a switchable lamellar antiferroelectric phase and a switchable columnar ferroelectric phase. Under a strong dc bias field they have collected some evidence of an increase in the range of stability of the SmCP phase and elimination of the columnar phase. More detailed dielectric and x-ray diffraction studies are underway to determine the structural changes under the applied field.

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 and phase behaviour of ionic amphiphiles with strongly bound counter-ions and polyelectrolytes among other questions in soft condensed matter physics. During the year gone by, his research has concentrated on

i) Determination of membrane rigidity from thermal fluctuations of lipid vesicles in collaboration with Buti Suryabrahmam and S. Madhukar (PhD students, RRI)
ii) Adsorption of polyelectrolytes on charged surfaces in collaboration with Meera Thomas (PhD student, RRI) and
iii) Tracer diffusion in supported lipid bilayers in collaboration with Sreeja Sasidharan (PhD student, RRI)

i) In the first work, the bending rigidity of lipid membranes has been determined from a detailed analysis of thermal fluctuations of giant unilamellar vesicles. The steps followed were

a) Obtaining the contours of vesicles from optical microscopy data, which are then decomposed into various fluctuation modes,

b) Membrane rigidity is then estimated from the mean square amplitudes of these modes. Preliminary results are in agreement with earlier reports in related areas.

ii) Effect of salt on the adsorption of polyelectrolytes on oppositely charged surfactant bi-layers has been studied. At low salt concentrations the polyelectrolyte is found to form a thin layer sandwiching adjacent bi-layers. As the salt concentration is increased the thickness of the poly-electrolyte film at first increases abruptly and then decreases very gradually. The reason for this behaviour is currently being investigated.

iii) In this third project, influence of the substrate on tracer diffusion in supported lipid bi-layers has been studied using the fluorescence recovery after photo bleaching technique. It is found that the presence of a polymer cushion on the substrate does not always increase the fluidity of the bi-layer, as is often assumed in the literature. Detailed experiments are underway to probe the interaction of the polymer cushion with the lipid bi-layer in order to understand tracer diffusion in these systems.

Arun Roy is primarily interested in soft condensed matter physics, phase transitions, electro-optics of liquid crystals, liquid crystal-nano-particle composites, Micro Raman spectroscopy and phenomenological theories of liquid crystals. Under the broader framework of phase transition and electro-optics of liquid crystals, during the previous year Arun has pursued research in the following problems:

i) Effect of smectic short-range order on the discontinuous anchoring transition in nematic liquid crystals in collaboration with Surajit Dhara Group (University of Hyderabad, Hyderabad) and W. Haase (Darmstadt University of Technology, Germany).

The alignment of molecules on the confining substrate is crucial for various applications of liquid crystals. Generally, two types of orientations are preferred for both LCDs and for physical measurements, namely, planar and homeotropic. In the planar state, the director (the average direction of molecular orientation) is parallel and in the homeotropic state the director is perpendicular to the substrates. There are various techniques for aligning liquid crystal molecules on the substrates. One common and inexpensive technique is coating of appropriate polyimidesto get the desired alignments (planar or homeotropic). It is known that the alignment of liquid crystal molecules depend upon topography of the surfaces, chemistry of the liquid crystals, aligning agents, curing temperatures, and the rubbing strengths. The commercial aligning agents provide stable director alignment in the sense that it does not change the molecular orientation with temperature. However, there are some reports that on some unconventional alignment layers, the director can change its orientation from planar to homeotropic and vice versa continuously or discontinuously with temperature. Such anchoring transition can have interesting applications in re-writable memory devices, optical wave guiding, tunable dielectric and conductive systems. However, the reason for discontinuous anchoring transition in these systems remained unexplored. Arun and his collaborators have studied the alignment properties of the homologous series of CCNs liquid crystals on perfluoropolymer-coated substrate. Interestingly, they have found that two compounds do not show any anchoring transition. The remaining four compounds exhibit strong discontinuous anchoring transition in the nematic phase with increasing thermal hysteresis. The experimental results suggest that the effect of smectic short-range order and the temperature range of nematic are important for the observed discontinuous anchoring transition. They have also developed a simple theory taking into account the short-range smectic order at the substrates that explains the experimental results. The results have been published in *J. Chem. Phys.*, **141** 044706 (2014).

ii) Structural invesigation of resorcinol based symmetrical banana mesogens by XRD, NMR and Polarization measurements in collaboration with T. Narasimhaswami's Group (Central Leather Research Institute, Chennai), K. V. Ramanathan (Indian Institute of Science, Bangalore) and B. Jacintha (Research Assistant, RRI).

The banana mesogens are a distinct class of molecular materials exhibiting fascinating liquid crystalline properties. The supra-molecular organization leading to a remarkable range of phase morphology and the formation of macroscopic chirality by spontaneous symmetry breaking are the two most important features of banana mesogens. The key molecular designing parameters for the construction of banana mesogens include structural variations of the central parts, the lateral substituents, the linking groups, the terminal chains, and the number of rings as well as the bent-angle between the wings. As a consequence, a large amount of work dealing with structural variations and their influence on mesophase properties has been reported in the literature. In light of the established molecular features, the current emphasis is placed more on understanding molecular level organization and its relation to molecular structure besides the synthesis of new molecules. In this work,

the synthesis and structural characterization of resorcinol based symmetrical seven phenyl ring banana mesogens with terminal dodecyl / dodecyloxy chains using x-ray diffraction, NMR, Polarising optical microscopy and electro-optic measurements have been reported. It has been observed that despite the structural similarity, the mesogens reveal many differences owing to the addition of just an oxygen atom on either side. The results have been published in *Phys. Chem. Chem. Phys.*, **17**5236-5247 (2015).

iii) Along with Deepshika Malkar (PhD student, RRI) Roy has performed experimental studies on unusual smectic phases exhibited by bent core hockey stick shaped molecules.

A typical bent core 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. Recently asymmetric bent core molecules in which the two arms or the chains attached to the ends of the molecule being different have also been found to exhibit new LC phases. However, in most of these asymmetric BC molecules, the asymmetry in the molecule is introduced by using different chain lengths or different linkage groups in the two arms of the BC molecule, with the length of the two arms of the BC molecule being comparable. Only few studies have been reported in which one of the arms is relatively shorter than the other arm of the molecule. This type of bent core molecules are denoted as bent-core hockey stick (BCHS) shaped molecules. Arun and Deepshika have experimentally investigated two unusual smectic phases exhibited by such BCHS molecules using x-ray diffraction, polarising optical microscopy and electro optic measurements. Based on the experimental results they are now trying to understand the molecular organisation in the layers.

iv) Experimental investigations on nucleation and growth morphology of dark conglomerate phase from the isotropic liquid in collaboration with Harsha Mohan Paroor (Postdoctoral fellow, RRI)

Recently a variety of simple bent-core molecules have been shown to exhibit a macroscopically isotropic fluids phase known as dark conglomerate (DC) phase possessing only short-range orientational and positional order. The DC phase is characterised by domains of macroscopically broken chiral symmetry-even though the constituent molecules are a chiral. Their conglomerate domains exhibit optical rotatory powers comparable to the highest ever found for isotropic fluids of chiral molecules. Though some structural characterisation of these phases are reported, the kinetics and growth morphology of the domains are not yet explored. Using polarising optical microscopy and high resolution imaging, Arun and Harsha are experimentally investigating the nucleation and growth morphology of these DC domains on cooling from the isotropic phase.

Arun's second research theme for the past year has been in the fabrication of electrochemically grown mesoporous metallic thin films for Surface Enhanced Raman Spectroscopic studies. He has worked alongside Anu Renjith (PhD student, RRI) and V. Lakshminarayanan (Emeritus Professor, RRI) in this project. They have developed a simple electro-deposition process of forming thin films of noble metallic nanoparticles in deep eutectic solvents (DES). The proposed method utilizes the inherent ability of DES medium to act as a reducing medium and also stabilizing the nanoparticles that are formed.

The mesoporous metal films have been characterised by SEM, XRD and electrochemical techniques. The potential applications of these substrates in Surface Enhanced Raman Spectroscopy (SERS) have also been investigated. A large enhancement of the Raman signal of the analyte was found on the mesoporous silver substrate after removing all the stabilizer molecules from the surface by calcination. Some of this work has been published in *J. Colloid Interface sci.*, **426** 270-279 (2014).

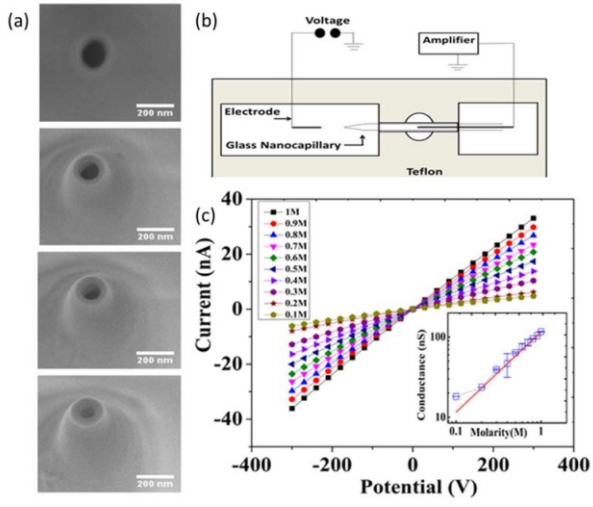
Gautam Vivek Soni's research interests are primarily guided by the intriguing synergy of structures in biological systems and their functional dynamics. He uses as well as develops novel nano-technological tools to decipher biophysical principles governing self-assembly of proteins and DNA-protein complexes such as chromatin fibers.

He has been successful in setting up a homemade nanopore platform in his lab in collaboration with Sharanya, Adwait, Mani, Arvind and Sourabha (Visiting students, RRI). His group developed glass nano-pores, one of the first groups in the world to do so. They now have the ability to routinely construct very low noise nanopores of sizes range 800-8nm. At present they are characterizing these nano-pores for their conduction properties. They have also started single molecule detection of individual DNA molecules trans locating through a nano-pore.

Soni is currently in long-term collaboration with Cees Dekker, Kavli Institute of NanoScience, Department of Bio-nanoscience, TU Delft and Don Cleveland at Ludwig Institute for Cancer Research, La Jolla CA.

During the previous year he has utilized the services of
(a) The RRI mechanical workshop to construct a Faraday box that will be extensively used for very sensitive nanopore based measurements.
(b) RRI SEM facility to characterize and image nano-capillaries using quartz tubes and
(c) RRI AFM facility extensively to characterize his DNA samples.
In the near future, he will be one of the regular users of a sub-micron resolution microfluidics fabrication facility being set up in the city.

The Figures below show
(a) Glass Nano pores (of various diameters) constructed in Soni's lab,
(b) Experimental electrical setup and
(c) Conduction measurements of these nanopores.



D. Vijayraghavan's areas of research interests are mainly in electrical, optical and diamagnetic properties of lyotropic liquid crystals, liquid crystal-nanoparticle composites and self-assembly of nano structures in liquid crystals. During the previous year his research consisted of an investigation into the self-assembled ordering of single-walled carbon nanotubes in a lyotropic liquid crystal system.

Carbon nano tubes possess high aspect ratio and exhibit high tensile strength and anisotropic electrical and thermal conductivities. Due to their unique features, they are expected to find applications in solar cells, sensors, and electrical and mechanical nano devices. However, to realize most of these applications, uniform alignment of carbon nano tubes is necessary. One way of aligning carbon nano tubes is to disperse them in liquid crystals as it is expected that the liquid crystals impose their orientational order on CNT guests. A uniform nanotube alignment was reported by dispersing CNTs in thermotropic liquid crystals. However, dispersion of individual nanotubes in thermotropic LC is not straightforward due to the bundling and aggregation of CNTs even for mild concentration of CNTs. On the other hand, in the case of water based LLCs a considerable amount of CNTs can be dispersed and aligned. Efficient dispersal and alignment of CNTs in LLCs are extensively reported in the literature. Weiss *et al* reported the insertion of CNTs in a hexagonal LLC and studied the alignment of CNTs in the LLC using light microscopy imaging and small-angle X-ray scattering techniques. Lager wall *et al.* have aligned the CNTs in the lyotro picnematic liquid crystals formed both by rod shaped and disc shaped micelles. Their polarized Raman spectroscopy measurements indicated that the nanotubes are aligned along the LC director. Notiv-Roth *et al.* dispersed SWCNTs in CTAB / water lyotropic liquid crystal system. They carried out SAXS and cryo-TEM studies on the dispersion. Moussa *et al.* reported high orientational ordering of SWCNTs when dispersed in a nematicchromonic liquid crystal.

Interestingly, except in the case of the SWCNTs dispersed in the nematicchromonic LLC, the reported studies on SWCNTs-LLC dispersions are carried out only at room temperature. The temperature dependence or the dynamics of the CNT alignment in LLC matrix had not been investigated in detail so far. It is believed that investigating CNT alignment in LLC as a function of temperature in various LLC phases and phase transition regions of the same LLC system will give interesting results. (Incidentally, it is reported that in the case of multiwalled CNTs dispersed thermotropic LCs, the optical transmission of the composite exhibits a step-wise change at the NI transition temperature, which is attributed to some structural ordering of nanotubes in the composite).Further, it is known that in the case of surfactant / water / CNTs systems, at high surfactant concentration, surfactant micelles induce aggregation of nanotubes due to an attractive interaction known as depletion attraction. It arises from the osmotic pressure formed by the surfactant micelles. It is believed that these attractive interactions can lead to the ordering of the nanotubes in the LLC. Motivated by the above, Vijayaraghavan has carried out SAXS, optical birefringence and electrical conductivity measurements as a function of temperature on a LLC-SWCNTs (0.01 wt%) composite. His LLC system consists of 25 wt% cetyltrimethylammoniumbromide (CTAB) in water. This LLC system exhibits crystalline surfactant + water (Cr), nematic (N), hexagonal (H) and isotropic (I) phases on heating. His SAXS studies revealed various self-assembled structures or ordering of SWCNTs depending on the phases of the LLC matrix. In the surfactant crystal + water phase of the LLC, the doped CNTs exhibit 1-D ordering. In the nematic and hexagonal phase

of the LLC, the CNTs exhibit 2-D hexagonal ordering. In the isotropic phase, there are domains of CNTs and within each domain the nanotubes exhibit 1-D ordering. The temperature dependence of the d-spacing of the SWCNTs showed peaks in the vicinity of the phase transition temperatures of the LLC. Interestingly, the temperature dependence of the optical birefringence and electrical conductivity of the composite also showed peaks at the phase transition temperatures. This indicates a correlation between the d-spacing of the SWCNTs and the observed anomalous increase in the birefringence and conductivity of the composite at the phase transition temperatures.

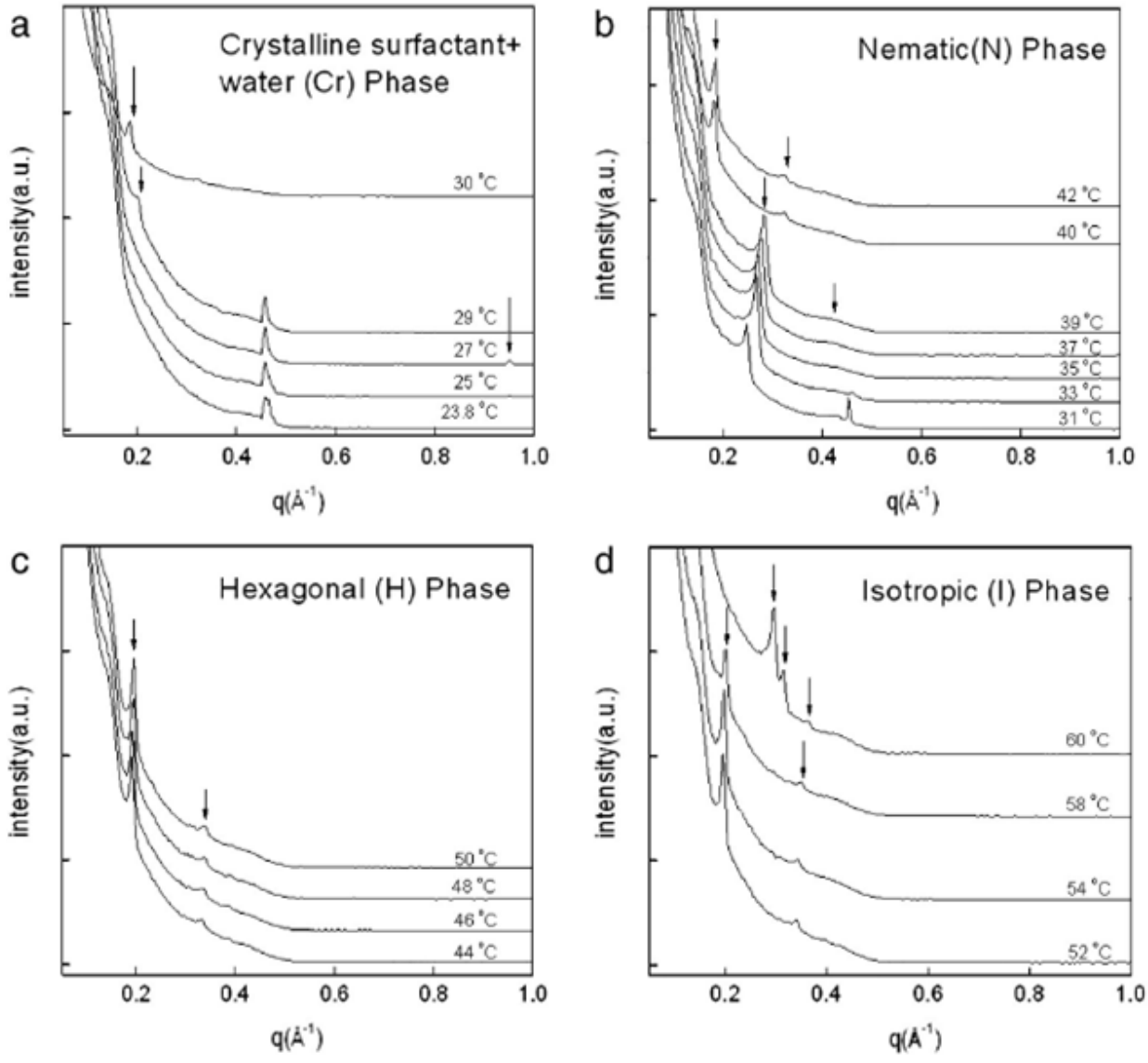


Fig. 1. SAXS patterns of SWCNT-LLC composite in different phases of the host LLC as a function of temperature. a) in the crystalline + water (Cr), b) nematic (N), c) hexagonal (H) and d) isotropic (I) phases. The arrows indicate the peak positions. [Image credit: D. Vijayaraghavan, (2014): Self-assembled ordering of single-walled carbon nanotubes in a lyotropic liquid crystal system, J. Mol. Liq. 199, 128-132]

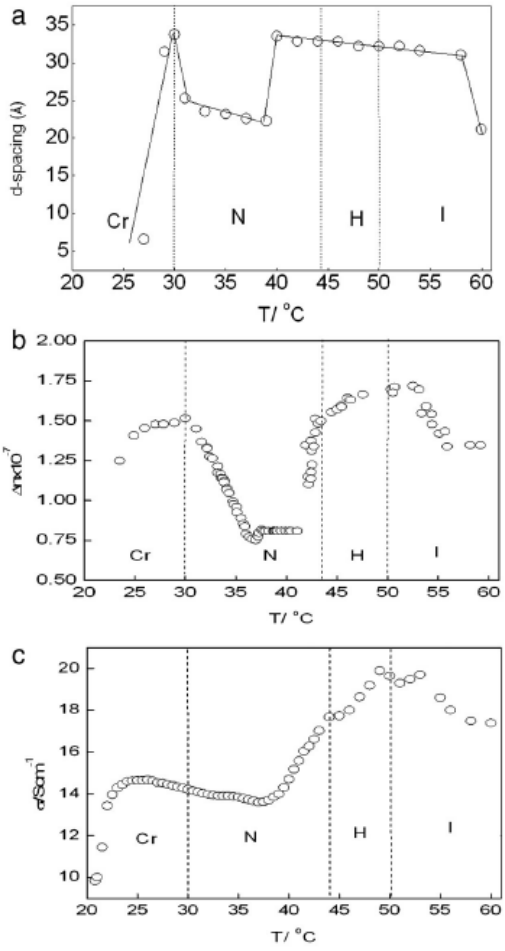


Fig. 2 a) d-spacing of the SAXS peaks of SWCNT-LLC composite as a function of temperature. b) Optical birefringence (∆n) of SWCNT-LLC composite as a function of temperature. c) Electrical conductivity (σ) of the SWCNT-LLC composite as a function of temperature. In all the cases, peaks are seen in the vicinity of the phase transition temperatures of the host LLC. It is believed that the broad peak in the vicinity of 50 °C may consist of two unresolved peaks corresponding to the nematic to hexagonal (44 °C) and hexagonal to isotropic (at 50 °C) phase transitions [Image credit: D. Vijayaraghavan, (2014) Self-assembled ordering of single-walled carbon nanotubes in a lyotropic liquid crystal system, J. Mol. Liq. 199, 128-132]

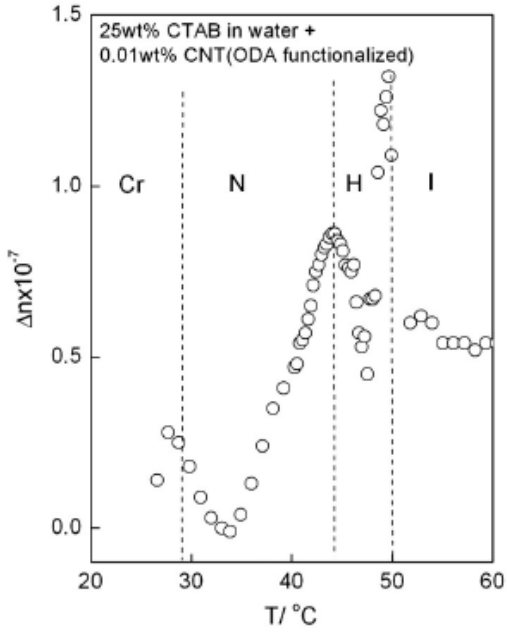


Fig.3 Temperature dependence of the optical birefringence (Δn) of octadecylammonium (ODA) functionalized SWCNTs dispersed LLC. Three distinct peaks (corresponding to the crystal to nematic, nematic to hexagonal and hexagonal to isotropic phase transitions) in the vicinity of the phase transition temperatures are seen. [Image Credit: D. Vijayaraghavan, (2014): Self-assembled ordering of single-walled carbon nanotubes in a lyotropic liquid crystal system, J. Mol. Liq. 199, 128-132]

Harsha Mohan Paroor's areas of current professional research interests are primarily in experimental Soft Matter Physics - dynamics at interfaces, phase separation, surfactant systems, micro emulsion, rheology of colloids, biomimectics and liquid crystals

During the period 2014-2015, collaborating with Ranjini Bandyopadhyay and Arun Roy (RRI), she has conducted birefringence studies on the interface induced anisotropy observed in aquoeus clay suspensions. In this work, she has studied the birefringence behavior occurring at the air-water interface of jammed, aqueous clay suspensions. Laponite, a synthetic clay, is composed of disk-shaped nanoparticles with diameters of 25-30 nm and a thickness 1 nm. Aqueous suspensions of Laponite form a soft solid that is not in thermodynamic equilibrium. Over days, they develop optical birefringence in the vicinity of the air interface that extends to the bulk. The birefringence extends to a distance that is several orders of magnitude larger than the particle length scale. Many groups have observed orientational order in aqueous clay suspensions but they essentially investigated the bulk behavior. An important question that still remains unanswered: Is it the air interface alone that initiates the orientation of the clay particles at the interface? Can the birefringence of the sample be measured directly, unlike the other research groups? Harsha and her collaborators have tried to answer these questions through their work.

The second major piece of work that Harsha has pursued is the study of phase transition properties of dark-conglomerate (DC) phases formed by achiral bent-core liquid crystal molecules with Arun Roy (RRI). They have experimentally studied the phase transition properties of dark-conglomerate (DC) phases formed by achiral bent-core liquid crystal molecules. The DC- phase that appears immediately below the isotropic phase is optically isotropic and exhibits spontaneous macroscopic chirality. The experiments reveal novel and unique features during the phase transition from isotropic phase to DC phase and vice versa. This phase that has a characteristic texture appears isotropic under crossed polarisers and reveals left-and right-handed chiral domains (appears black and white in contrast) when the polarisers are decrossed [Fig 6].

For the first project, Harsha has used a home-built set up to measure the mild birefringent property of the sample. This was based on lock-in detection, to measure the mild birefringence and hence the ordering in clay suspensions. This is achieved using a photo elastic modulator (PEM), whose retardation axis defines the 0^0 for the coordinate system of the setup [Fig 1].

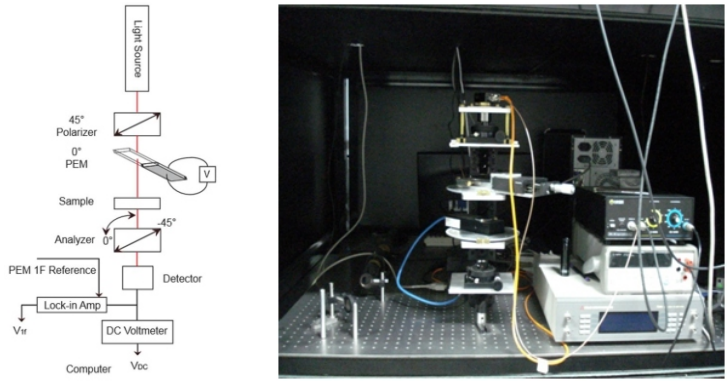


Fig 1: Schematic diagram (left) and the actual setup (right) built in-house for studying the height dependent extension of the orientational ordering in aqueous Laponite suspensions.

This home-built experimental setup is calibrated using a known liquid crystalline sample, 5CB. The birefringence of the 5CB is 0.15. The birefringence data of the sample measured using the setup for different trials is shown in Fig 2. The data shows the high reproducibility of measurements using our setup.

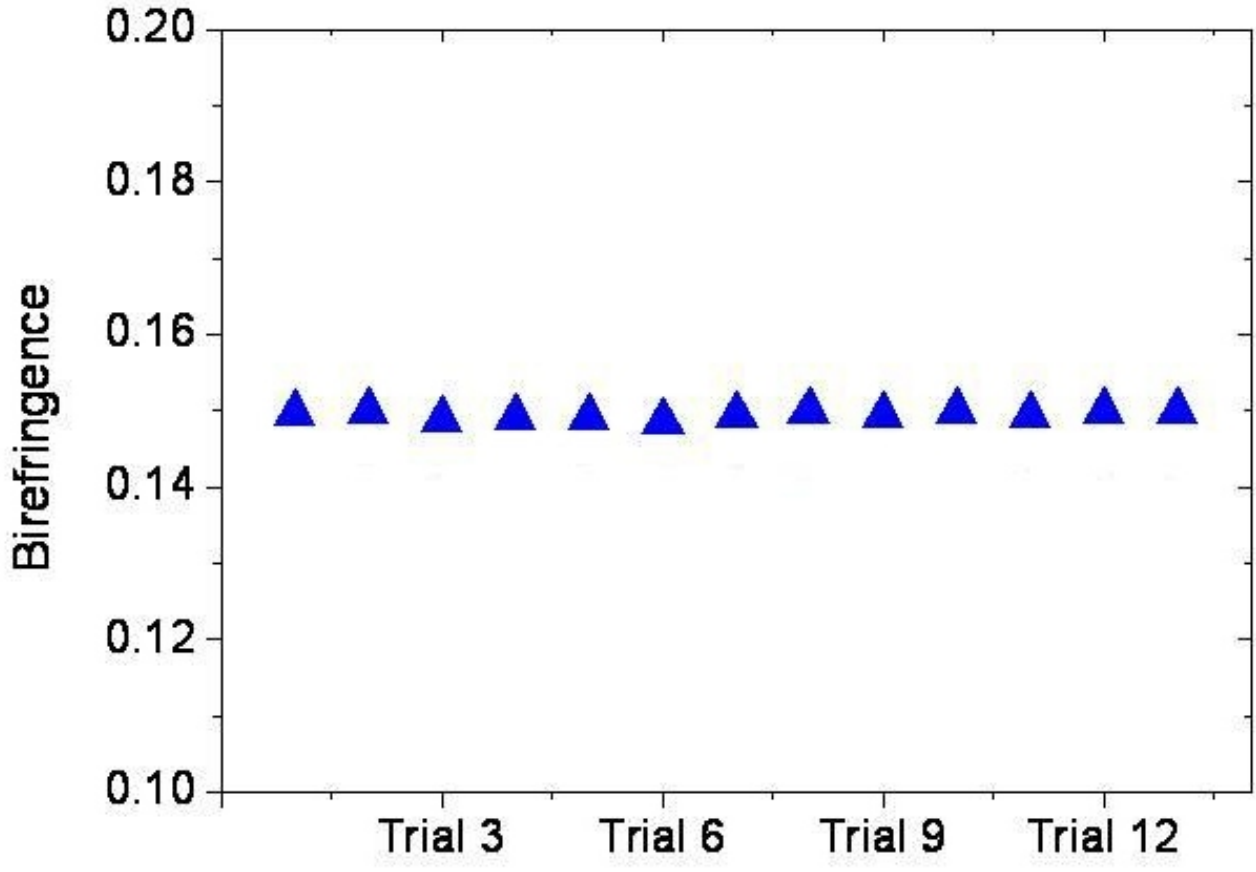


Fig 2: Birefringence of 5CB measured at various trials using the home-built setup is shown by blue triangles.

Aqueous Laponite suspensions are the model clay suspensions being used for the experiments. The influences on the orientational ordering by the different pH, different cluster size and the dissolution of air in the sample are investigated. A few of final data of retardation properties against the distance from the air-water interface of the sample are shown below.

The retardation properties of the sample are studied with varying cluster size of studied with varying cluster size of the clay [Fig 2], pH [Fig 3] and dissolution of the air [Fig 4]. In Fig. 3, they have studied four samples with different cluster size. Filters with different pore size have been used to achieve this. Retardation of all samples are measured for different ageing of 10 days, 15 days and 18 days. Retardation from the air-water interface for the four different samples showed similar trend. But a non-monotonic behaviour is observed for data with ageing as well as with the distance from the interface.

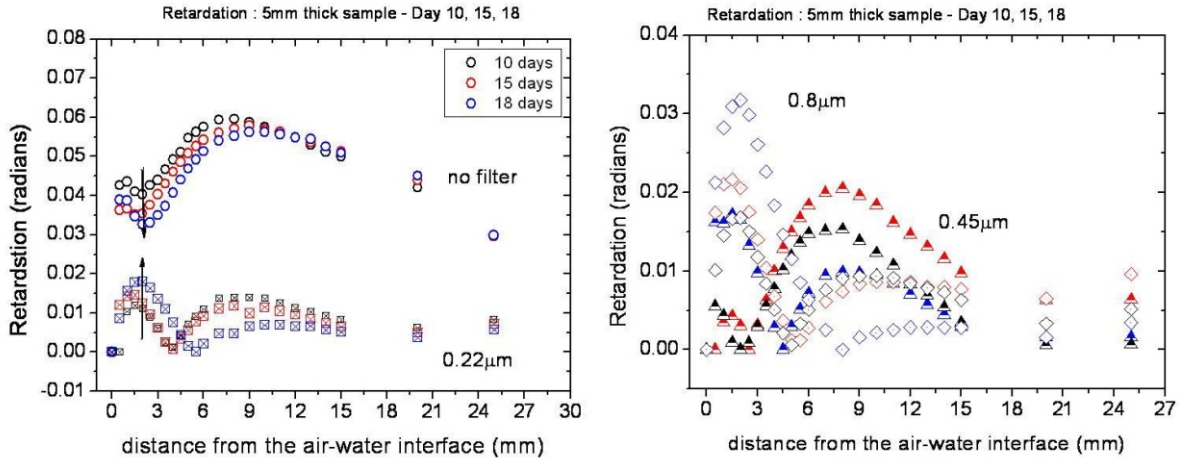


Fig 3: Cluster dependent sample retardation of aqueous Laponite suspension. Data has been taken from the air-water interface of the sample to the bulk along the sample length. Retardation for 10 days (black), 15 days (red) and 18 days (blue) of ageing are also recorded.

Fig. 4 shows the birefringence data for laponite samples with two different pHs, 12 and 13. An increase in birefringence is observed with increase in pH. Though the data as shown in Fig 4, seems scattered for higher pH samples.

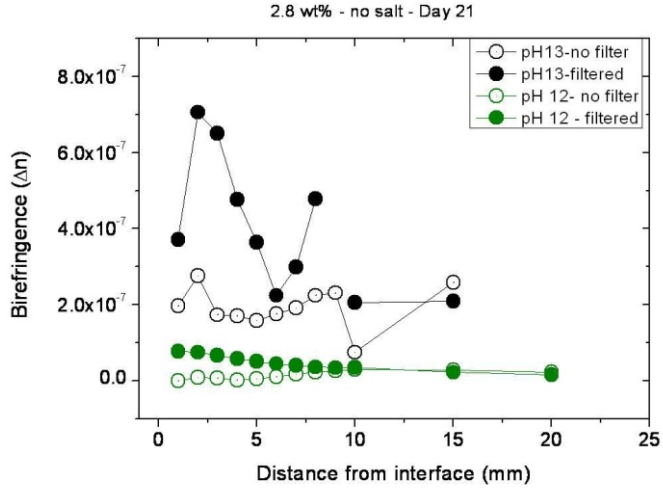


Fig 4: pH dependent sample retardation of aqueous Laponite suspension. Filtered (solid circles)as well as unfiltered (open circles) samples with pH 12 (green) and pH 13 (black) are used.

Influence of the dissolved air in the sample is shown in Fig 5. Samples are prepared with and without dissolved air in it using a vaccum chamber. Initially (week 3) samples with air were more birefringent at the interface than the samples without air (left). Later (week 12), samples without air became more birefringent as shown in the figure 5.

Although as shown above, they have been able to measure the birefringence of the clay suspensions, the non-monotonic behaviour of the data from the clay suspension still remains to be understood.

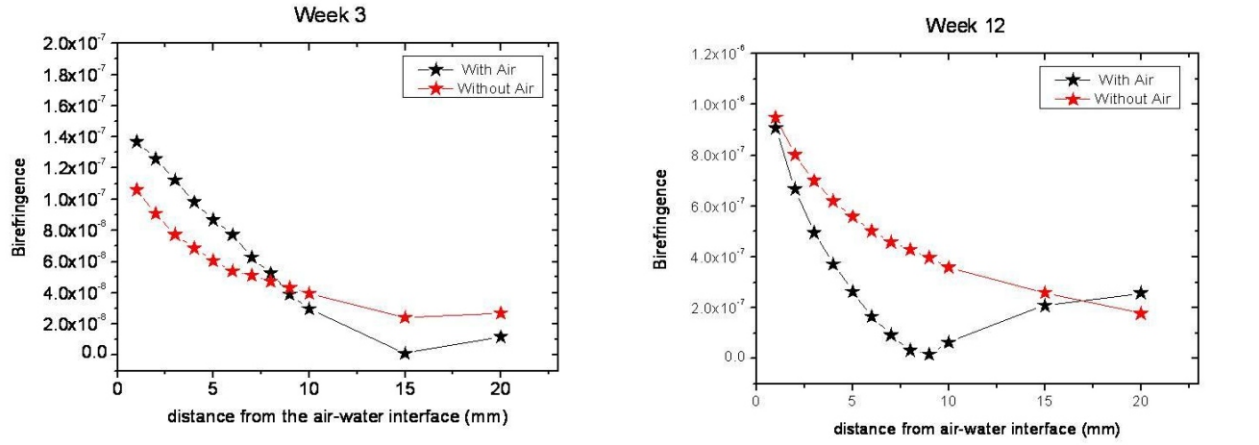


Fig 5: Influence of dissolved air in the sample towards sample retardation of aqueous Laponite suspension. Birefringence for samples with air (black stars) and without air (red stars) is shown.

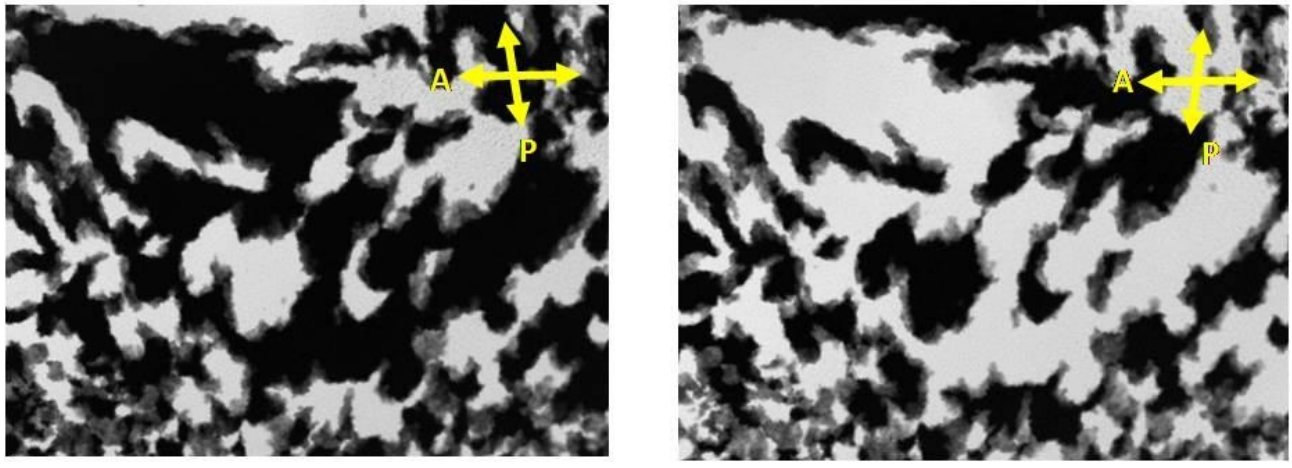


Fig 6. Texture of left- and right- handed chiral domains observed with decrossed polarisers (here 4^0) on cooling.

In her second project, Harsha's experiments report unique features during the phase transition from isotropic phase to DC phase and vice versa [Fig 7]. A transition from isotropic to DC phase happens with the nucleation and growth of dark and white domains (Fig 7). DC phase nucleates as seeds and grow as fractals, which is unlike other liquid crystals. Harsha and Roy are now investigating the fractal growth dynamics during phase transition. Images and videos are taken using a Nikon polarising microscope with a CCD attached. Analysis of the dark and white domains of the DC phase showed an equal contribution of the domains. Further investigations of this unique feature are ongoing and promising.

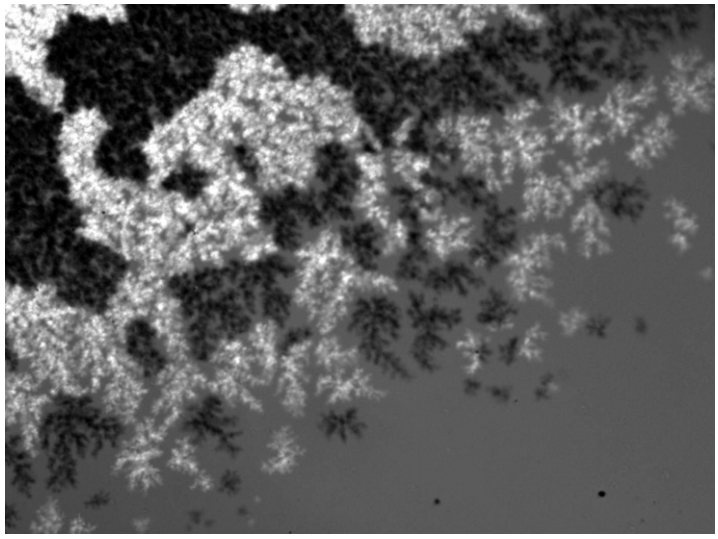


Fig 7: Images of temperature-dependent phase transition in bent-core molecules in a temperature range of 133^{0}C to 108^{0}C. Cooling of isotropic phase leads to DC-phase with an interface of fractals (left image).

Pramod Tadapatri's research interests mainly lie in studying electric field effects of liquid crystals and optical and dielectric studies of polyelectrolytes.

During the period of this report, he has investigated field induced phase transitions in a bent core liquid crystal in collaboration with R. Pratibha (RRI). Last two decades of liquid crystal research largely belongs to the unusual phase behaviour of banana or bent-core molecules. This novel area arises from the compact packing arrangement of these molecules that restricts rotational freedom allowing the molecules to organize into novel types of liquid crystalline phases. Vorlander was the first to synthesize bent-core molecules. As they were not standard rods, they were not characterized. However, a breakthrough came in 1996 when Niori *et al.* reported a ferroelectric switching behaviour in a compound composed of achiral bent-core molecules. The bent-core molecules are strongly polar and biaxial in shape and thus strongly deviate from cylindrical symmetry. Liquid crystalline phases formed by bent-core molecules are nematic, lamellar and columnar phases. These phases are different from those exhibited by rod-like and disc-like molecules.Along with classical nematic and smectic phases, these bent-core liquid crystals are known to exhibit several new mesophases designated as B1, B2....B8 with B standing for bent-core or banana molecules. Some of the interesting phases are polar smectic phase (SmCP), orthogonal smectic phase (SmAP), reversed columnar phases (B1rev and B1revtilt) and dark conglomerate (DC) phases. These phases are unique starting from their molecular structure to various other properties.

The field induced phases arising in BC molecules has caught the attention of researchers in this field recently. There are instances in literature showing transition from lamellar to columnar phases under applied electric field. But the transition from columnar to lamellar phases is very rare. These transitions provide an insight into the underlying structure of the phases. In search of such interesting transitions, Tadapatri and Pratibha have taken up the study of an achiral seven-ring bent core compound derived from 5-methoxyisophthalic acid (SRC14) which shows a field-free transition from the switchable lamellar B2 (SmCP) phase to

switchable columnar B1rev phase. In the columnar phase, the direction of spontaneous polarization in the broken-layer can be either perpendicular to the column axis (the B1 phase) or along the column (the B1rev phase). The B1rev phase with polarization along the column exhibits switching phenomena. Especially, the polarization values in this phase are very low (< 100 nC/cm^2) compared to earlier studies. These switching characteristics are determined by subjecting the sample to a triangular wave electric field coupled with a resistor. Then the corresponding current peaks generated through resistor in the circuit are monitored in an Oscilloscope (Agilent 54621A). The effect of dc bias on the dielectric permittivity values across the two phases is under investigation.

The second major project for Tadapatri during the year gone by was dielectric studies of single stranded DNA. A large number of previous studies show that the ion atmosphere around polyions (like DNA here) in aqueous solution consists of two portions, namely the condensed and diffused phases. Counterions diffuse and bind to the polyions from the surrounding electrolyte solution to reduce the strong Coulomb repulsion between the negatively charged phosphate groups, resulting in the formation of the condensed phase. In addition, the diffused phase of loosely bound counterions is formed surrounding the condensed phase in order to shield the charges of the residual phosphate groups. The dielectric dispersion of a polyelectrolyte solution originates in the relaxation of the polarized ion atmosphere. A difficulty in testing counter ion theories of polyelectrolytes by means of dielectric spectroscopy is addressed to the lack of lack of sensitivity in detecting the small dielectric increment for an extremely dilute solution in which the interaction among the polyions is negligibly small. Further, the theories governing these phenomena only deal with the polarization of condensed counter ions or the polarization of loosely bound counterions with the thin double-layer approximation, and no systematic verification has been experimentally made for the effects of the spatial extent of the diffused phase. Therefore, it would be interesting to examine the influence of the spatial distribution of counterions on the dielectric properties of polyions, controlling the thickness of the ion atmosphere by systematically changing the solute and salt concentrations. Synthetic single-stranded DNA (ss-DNA) of length 60 and 100 bases was purchased. Most of the other reports conducted dielectric experiments only upto the concentration 0.1 g/l. To explore dielectric behaviour at much more diluted solutions (<0.1 g/l) Tadapatri and his collaborators, R. Pratibha (RRI) and M. Muthukumar (University of Massachusetts) have confirmed the initial concentration by performing the Nanodrop experiment. Also, they have observed the standard UV absorbance peak at ~260nm. Dielectric spectra were recorded using Novo control Alpha-A analyzer connected with ZG4 interface. The advantage here is that the Novo control analyzer can go to μHz frequencies with good accuracy even at such frequencies compared to other analyzers. A liquid dielectric cell with parallel Platinum electrodes was used. A third reference electrode (Ag/AgCl electrode) was introduced to compensate polarization effects of the electrodes. Interestingly, experiments on 3 concentrations reveal unseen relaxation modes at very low frequencies (<1Hz). The variation of relaxation frequencies with various salt concentrations will be explored in future.

THEORETICAL PHYSICS

Overview

The major areas of research pursued by the Theoretical Physics (TP) group include statistical physics, soft matter physics (including physics in biology), gravitational waves, quantum gravity and general relativity and foundations of quantum mechanics. There are interfaces between the LAMP and SCM groups and collaborations with experimentalists working in the areas of foundational questions in quantum physics and biophysics, both within and outside the institute.

Statistical Physics

A theoretical and experimental understanding of heat and electron transport processes in systems of mesoscopic (a few microns to the size of a single atom) scale are fundamentally important to improve the performance of nano-devices and their applications. To this end research is carried out by the TP group on the transport of heat and electricity using the Langevin equation and scattering approaches. The role of disorder, nonlinearity and dissipation on the transport properties of such systems are also under investigation. Analytical work starting from first principles, on understanding the mechanical response of amorphous and crystalline solids (elastic media) to large deformations, nucleation dynamics and dynamics of solid-solid transformations is also being pursued at RRI at the moment. The equilibrium and dynamical properties of polymers is another area of soft condensed matter research that the TP group is currently engaged in. In this area, there are several experimental groups, which can bend and twist DNA molecules to study their elastic properties. The packaging of DNA in the cell nucleus is one of the motivations for the study. The work from the TP group addresses elastic properties of semi-flexible polymers over a range of stiffness. Using the concept of geometric phase, a simple theoretical model has been arrived at that captures a range of molecular elastic properties in polymers, from DNA to action. Similarly the role of thermal fluctuations on the elastic response of bent and twisted ribbons is expected to shed light on DNA looping "J Factor" and on the bending elasticity of twisted graphene ribbons. The above studies can be viewed as an application of the methods of theoretical physics to biology.

Non-equilibrium statistical mechanics is another field of interest for the TP group. Large deviations, probability and statistics of rare and extreme events or driven systems are some of the problems being explored currently within this realm. Examples of such problems being explored in the past one year include universal large deviations for a tagged particle in single-file motion, tagged particle diffusion in one-dimensional systems of interacting point particles evolving under Hamiltonian dynamics and fluctuations of the work done by an external correlated random force on a Brownian particle in a given time interval in the steady state. Driven inelastic Maxwell gases, which consist of a collection of particles characterised only by their velocities, and evolving through binary collisions and external driving, have also been investigated by the TP group during the period 2014-2015. The system is found to reach a steady state under specific conditions such as the type of driving and the value of the coefficient of restitution for collision between the driven gaseous particles.

A stochastic process, when subject to resetting to its initial condition at a constant rate, generically reaches a non-equilibrium steady state. The TP group is analytically studying various stochastic processes under resetting conditions. Specific questions being addressed include studies on how the steady state is approached in time by a resetting stochastic system and Levy flights with optimal search times that show a remarkable first order transition in the optimal parameters allowing for a successful search. In the former case, researchers find a dynamical transition occurring in the relaxation mechanism of these systems. These apart, issues pertaining to jamming of granular matter and onset of shear waves in a bacterial bath are also being addressed using

techniques typical to non-equilibrium statistical physics.

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. Also applications of LQG ideas to solve a truncated space of homogeneous and isotropic (cosmological) gravitational fields are being actively pursued through studying simpler covariant toy models. Recently the Koslowski-Sahlmann (KS) representation has been studied extensively by the TP group. KS representation is a generalization of the representation underlying the discrete spatial geometry of LQG particularly to accommodate states labelled by smooth spatial geometries. The KS representation has been shown by the TP group to support not only the holonomy and flux operators but also those that are the quantum counterparts of connection dependent "SU(2)" electric fields called "background exponential operators". The latest contribution to this field by RRI has been an explanation of the quantum kinematics for asymptotically flat space-times using the above representation.

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, both 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. An important result in numerical simulations for full 2D causal set quantum gravity using the RRI cluster is that the space time continuum is emergent. Most recently, research at RRI on these topics has led to some key insights like spatial homogeneity of the Hartle-Hawking no-boundary wave function for CST over the discrete analogues of space-like hyper-surfaces at low temperature – indicating a possible role of quantum gravity in shaping 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 generalisations. Work is on at RRI to understand how this framework can be used to obtain covariant observables in quantum gravity.

As an example of the multi-faceted research being carried out by the TP group we have a research problem that explores in detail the analogy between quantum gravity effects that cost too high an energy and are thus unfeasible to test out in a standard laboratory, with the fluctuating surface tension of micron sized fluid membranes. The background to the problem involves the smallness of the cosmological constant, or the dark energy that drives the expanding universe. It has been suggested that quantum gravity fluctuations could lead to this smallness and thus the need to probe more closely quantum gravity effects experimentally. This makes the aforementioned analogous study of surface tension a topic of fundamental importance in the field.

Quantum Measurements and Quantum Entanglement

During the period 2014-2015, the TP group at RRI has arrived at an extremely important result with far-reaching consequences in the measurement of time and the degree of accuracy that can be achieved in its measurement. It turns out that there is a fundamental limit to the measurement of time, set by a combination of three basic physical principles – uncertainty relation, gravitational redshift and relativistic time dilation effects. This result is expected to find large-scale applications in the designing of better clocks that are important in astronomy, metrology and global positioning 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.

General Relativity

Laser interferometer gravitational wave detectors like LIGO and VIRGO with their

remarkable sensitivity to wave signals from distant astrophysical sources have sparked off dedicated research in the calculation of gravitational waveforms from in spiralling super massive black hole binaries. The wave signals received by LIGO and VIRGO are, however, weak and heavily noise-ridden, which in turn intensifies the need for accurate templates to compare and cross-correlate with the data. The TP group at RRI examines this signal detection using future space based gravity-wave detectors like LISA and performs a complete and detailed study of the entire waveform. Taking into account the entire waveform ensures improved angular resolution for super massive black hole binaries and the data obtained is able to achieve a consistency with the dark energy equation of state to within a few percent.

Theorist's Laboratory

This is a forum for theorists to dirty their hands with simple table-top experiments and have better clarity in understanding certain fundamental aspects of theoretical physics through designing and performing such experiments. There have been experiments to study the mechanics of vibrated grains, the Marangoni effect between two interacting fluids and Brownian motion in milk globules. Several demonstrations using simple materials such as a rotating cube, an Archimedian screw pump, soap films and soap bubbles and concepts such as the effect of low Reynold's number, surface tension etc. on fluid motion have also been made at the Theorist's Laboratory. Recently, there have also been some polymer stretching experiments with theraband strips, using a setup put together with the help of the RRI workshop, with a view to understanding similarities between such experiments and molecular scale bio-polymer stretching experiments. The overall aim of the Theorist's Laboratory at RRI is to build a solid ground in understanding key theoretical concepts.

Bala Iyer's research interests lie mainly in General Relativity and Gravitational Waves. During the period of this annual report, Iyer has concentrated on the calculation of 3.5PN accurate spherical harmonic modes for in spiralling compact binaries in quasi-circular orbits along with Anil Tolamatti (Visiting student, RRI). In this context, work has been initiated for the computation of amplitude corrections at 3.5PN order for inspiralling compact binaries moving in quasi-circular orbits by restricting to multipoles which require only radiative moments up to 1.5PN order ie corresponding to multipolar orders from l=5 to l=9.

Narendra Kumar's research interests are generally in Anderson localization, superconductivity, randomness and complexity, fluctuation-dissipation, and decoherence in condensed matter – quantum as well as classical.

During the year gone by, he, along with V. Ranjith (RRI) studied light transmission through an ultra-slow-wave optical medium and its resulting complete stoppage. As part of this study, light-wave transmission – its compression, amplification, and the optical energy storage – in an Ultra Slow Wave Medium (USWM) has been studied analytically. A phenomenological treatment based entirely on the continuity equation for the optical energy flux, and the well known distribution-product property of Dirac delta-function has been applied to the problem at hand. The results so obtained provide a clear understanding of some recent experiments on light transmission and its complete stoppage in an USWM.

Ranjith and Kumar also worked on tight-binding models that render 'Quantum First Passage Time' speakable. The calculation of First Passage Time (andits Probability Density) has been generally viewed as an ill-posed problem in the domain of Quantum Mechanics (QM). The reasons for this have been often summarily attributed to the violation of the Kolmogorov Sum rule for probabilities in QM: The probability for entering and non-entering Feynman paths into a given region of space-time does not, in general, add up owing to the interference effects between the two. Here, we present a family of quantum systems, namely the 1D tight-binding Hamiltonian systems, wherein this interference terms drop out, rendering thus the first-passage time problem "speakable". With this premise, we have suitably used a method, due originally to Schroedinger (in 1915), to calculate first-passage time distribution exactly for our model system. This seems very interesting, especially given the fact that the tight-binding models are extensively used to describe real phenomena in condensed matter.

Along with Santanu Das (RRI), Kumar has looked into the discrete, the continuous and the "concrete" aspects of classical harmonic dynamics. An elementary treatment of classical harmonic dynamics of a linear (1D) array of identical point-like masses with equal couplings (elastic spring constants) is re-considered in three distinct limits – the discrete, where the mass-points are identical and equi-spaced while the springs are massless; the continuous, where the points are mass-full and uniformly distributed in the 1D elastic medium; and the "concrete" lattice that comprises continuously distributed *elastic couplings with non-zero mass-density* (per unit length) and embedded with equi-spaced identical mass-points – all along the 1D system. Analytical expressions are obtained for some elementary but rather subtle

Ongoing Research

quantities of physical interest – specially, the mechanical power transported across any arbitrarily chosen site, and the associated mechanical momentum along such an apparently simple purely oscillating 1D harmonic system. This classroom exercise concludes with a suggestion for the possibility that the "concrete" case may well correspond to the hard nanoparticulate crystallites embedded in a 1D elastic continuum, e.g., a spider dragline silk, which is known for its exceptionally fast vibrational energy transport, comparable to that of a diamond.

Madan Rao's research interests currently concentrate on non-equilibrium statistical mechanics, soft & biological matter, biology and information theory and control theory.
During the previous academic year, Rao's research comprised of broadly two categories: A) Understanding the mechanical behaviour of elastic media (amorphous and crystalline solids) from first principles. B) Understanding the mechanics of living systems (cells and tissues) at different scales, how this helps in organizing molecules, and their implications for the management of information and homeostatic control.

Under the first theme, Rao has worked on

(i) Understanding the mechanical response of amorphous and crystalline medium to large deformations and
(ii) Nucleation dynamics and dynamics of solid-solid transformations. This work has been done in collaboration with Surajit Sengupta(TCIS-TIFR, Hyderabad).

Under the second theme, Rao has worked on the following major problems -

(i) Studying molecular transport through the secretory pathway in cells (with Pierre Sens at ESPCI, Paris),
(ii) The biogenesis of organelles using non-equilibrium physics models (with Mustansir Barma at TIFR, Mumbai),
(iii) The dynamics of morphology of organelles driven out of equilibrium by active processes of fission and fusion (separate collaborations with Sunil Kumar, IIT-Madras and Pierre Sens, ESPCI, Paris).
(iv) Active mechanics of membranes, polymers, fluids, solids etc (some involving collaborations with Sriram Ramaswamy, TCIS-TIFR, Hyderabad).
(v) Active Composite cell surface (with Satyajit Mayor, NCBS)
(vi) Cell mechanics, Information processing and computation (with Garud Iyengar, Columbia University, USA, Sandeep Krishna, NCBS, Satyajit Mayor, NCBS) and
(vii) Active Tissue mechanics (with Thomas Lecuit, Univ. of Marseilles, France).

Rao and his group have used the RRI computing cluster to do atomistic MD simulations of multi-component membranes to test some of their ideas on the Active Composite Cell surface Model. These simulations have been very illuminating and have fetched important publications. The group has also used the RRI computing facility to study transport problems in a crowded cellular environment (Monte Carlo simulations) and in solving partial differential equations that arise in the dynamics of active fluids and active elastomers.

Sanjib Sabhapandit's research interest is in statistical physics. In the previous year, his research has concentrated on mainly the following themes –

a) Tagged particle diffusion in one-dimensional systems with Hamiltonian dynamics, with collaborators, Anjan Roy (PhD student, RRI), Abhishek Dhar (ICTS, TIFR), and Onuttom Narayan (University of California, Santa Cruz)

b) Universal Large Deviations for the Tagged Particle in Single-File Motion, with Chaitra Hegde (PhD student, RRI) and Abhishek Dhar,

c) Work fluctuations for a Brownian particle driven by a correlated external random force, with Arnab Pal (PhD student, RRI)

d) Driven inelastic Maxwell gases, with collaborators, V. V. Prasad (PhD student, RRI) and Abhishek Dhar

e) First order transition for the optimal search time of Levy flights with resetting, with Lukasz Kusmierz (Institute of Physics, Krakow, Poland), Satya N. Majumdar, and Gregory Schehr (Univ. Paris-Sud, CNRS, LPTMS, Orsay) and

f) Dynamical transition in the temporal relaxation of stochastic processes under resetting, in collaboration with Satya N. Majumdar and Gregory Schehr.

Under theme

(a) Sanjib along with his collaborators have studied various temporal correlation functions of a tagged particle in one-dimensional systems of interacting point particles evolving with Hamiltonian dynamics. Initial conditions of the particles are chosen from the canonical thermal distribution. The correlation functions are studied in finite systems, and their forms examined at short and long times. Various one-dimensional systems are studied. Results of numerical simulations for the Fermi-Pasta-Ulam chain are qualitatively similar to results for the harmonic chain, and agree unexpectedly well with a simple description in terms of linearized hydrodynamic equations for sound waves. Simulation results for the alternate mass hard particle gas reveal that the diffusion constant slowly converges to a constant value, in a manner consistent with mode-coupling theories. The simulations also show that the behaviour of Lennard-Jones gas depends on its density. At low densities, it behaves like a hard-particle gas, and at high densities like an anharmonic chain. In all the systems studied, the tagged particle was found to show normal diffusion asymptotically, with convergence times depending on the system under study. Finite size effects show up at time scales larger than sound traversal times, their nature being system-specific.

(b) The motion of particles in narrow channels where the particles cannot over take each other is referred to as single-file motion. The motion of a tagged particle in such a single-file system has been of great interest. It has been known from earlier theoretical works that in a gas of particles evolving with Hamiltonian dynamics, a tagged particle moves diffusively with the mean square displacement (MSD) growing linearly with time, whereas for a gas of Brownian particles, the tagged particle shows sub-diffusion with the MSD growing as the square root of the time. There has been a revival of interest in tagged particle diffusion, as several experiments have been able to show this in both colloidal and atomic single-file systems, and some of the theoretical predictions have been verified.

In Sanjib's recent work, they have considered a single-file system of a gas of point particles moving in a one-dimensional channel with a hard-core inter-particle interaction that prevents particle crossings. Starting from equilibrium initial conditions they have observed the motion of a tagged particle. They have computed the exact large deviation function for the tagged particle displacement and shown that this is universal and independent of the individual dynamics.

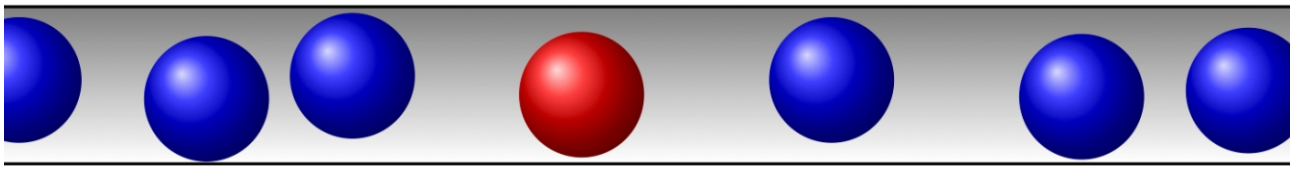


Fig. 1: A schematic diagram of single-file motion of particles in a narrow channel where they cannot pass each other. The motion of a single tagged particle (say, the red colored one) only is studied. [Image credit: Chaitra Hegde, Sanjib Sabhapandit, and Abhishek Dhar, (2014): Universal Large Deviations for the Tagged Particle in Single File Motion, Phys. Rev. Lett. 113, 120601]

Under theme

(c) Sanjib along with his collaborator have considered the under-damped motion of a Brownian particle in the presence of a correlated external random force. The force is modelled by an Ornstein-Uhlenbeck process. They investigate the fluctuations of the work done by the external force on the Brownian particle in a given time interval in the steady state and calculate the large deviation functions as well as the complete asymptotic form of the probability density function of the performed work. They have also discussed the symmetry properties of the large deviation functions for this system. Finally numerical simulations are found to be in very good agreement with the analytic results.

(d) An in elastic driven Maxwell gas consists of a collection of particles that are characterized by only their velocities, and evolving through binary collisions and external driving. At any instant, a particle is equally likely to collide with any of the remaining particles. The system evolves in continuous time with mutual collisions and driving taken to be point processes with rates τ_c^{-1} and τ_w^{-1} respectively.The mutual collisions conserve momentum and are inelastic, with a coefficient of restitution r. The velocity change of a particle with velocity v, due to driving, is taken to be $\Delta v = -(1 + r_w)v + \eta$, mimicing the collision with a vibrating wall, where r_w the coefficient of restitution of the particle with the "wall" and η is Gaussian white noise. The Ornstein-Uhlenbeck driving mechanism given by $\frac{dv}{dt} = -\Gamma v + \eta$ is found to be a special case of the driving modeled as a point process. Using both the continuum and discrete versions we show that while the equations for the one-particle and the two-particle velocity distribution functions do not close, the joint evolution equations of the variance and the two-particle velocity correlation functions close. With the exact formula for the variance we find that, for $r_w \neq -1$, the system goes to a steady state. On the other hand, for $r_w = -1$, the system does not have a steady state. Similarly, the system goes to a steady state for the Ornstein-Uhlenbeck driving with $\Gamma \neq 0$, whereas for the purely diffusive driving ($\Gamma = 0$), the system does not have a steady state.

Under theme

(e) Sanjib along with Lukasz Kusmierz (#), Satya N. Majumdar ($), and Gregory Schehr have studied analytically an intermittent search process in one dimension. There is an immobile target at the origin and a searcher undergoes a discrete time jump process starting at $x_0 > 0$, where successive jumps are drawn independently from an arbitrary

jump distribution f (η). In addition, with a probability 0 ≤ r <1, the position of the searcher is reset to its initial position x_0. The efficiency of the search strategy is characterized by the mean time to find the target, i.e., the mean first passage time (MFPT) to the origin. For arbitrary jump distribution f (η), position x_0 and resetting probability r, the MFPT is computed analytically. For the heavy-tailed L´evy stable jump distribution characterized by the L'evy index0 <μ<2, we show that, for any given x_0, the MFPT has a global minimum in the (μ,r) plane at (μ^* (x_0); r^*(x_0)) [See Fig. 2]. They find a remarkable first-order phase transition as x_0 crosses a critical value x_0 at which the optimal parameters change discontinuously. The analytical results are also in good agreement with numerical simulations.

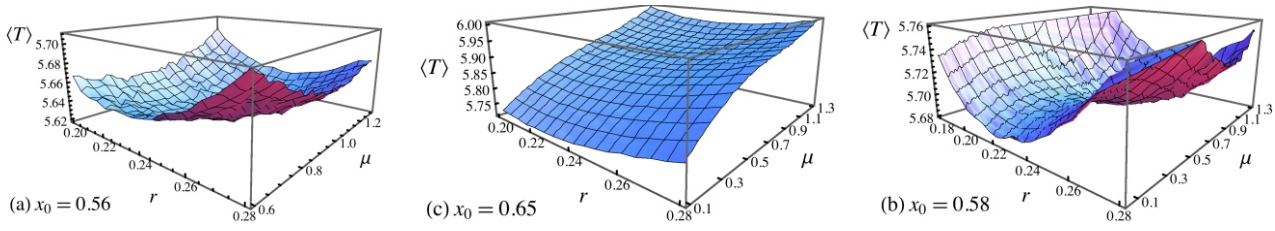


Fig. 2: Plots of the average search time < $T_{x_0}(\mu,r)$> computed using numerical simulations, in the (μ, r) plane for different values of the initial position x_0: (a) x_0= 0:56 <x_0^*, (b) x_0=x_0^* ≃ 0.58 and (c) x_0 = 0.65 >x_0^*[Image credit: Lukasz Kusmierz, Satya N. Majumdar, Sanjib Sabhapandit, and Gregory Schehr, (2014): First order transition for the optimal search time of L´evy flights with resetting, Phys. Rev. Lett. 113, 220602]

(f) A stochastic process, when subject to resetting to its initial condition at a constant rate, generically reaches a non-equilibrium steady state. Sanjib and his collaborators have analytically explored how the steady state is approached in time and they have found an unusual relaxation mechanism in these systems.

As time progresses, an inner core region around the resetting point reach steady state, while the region outside the core still remains transient. The boundaries of the core region grow with time as power laws at late times with new exponents [see Fig. 3]. Alternatively, at a fixed spatial point, the system undergoes a dynamical transition from the transient to the steady state at a characteristic space dependent timescale t*(x). They have analytically calculated in several examples the large deviation function associated with this spatio-temporal fluctuation and show that generically it has a second order discontinuity at a pair of critical points characterizing the edges of the inner core. These singularities act as separatrices between typical and atypical trajectories. All results have also been verified by numerical simulation.

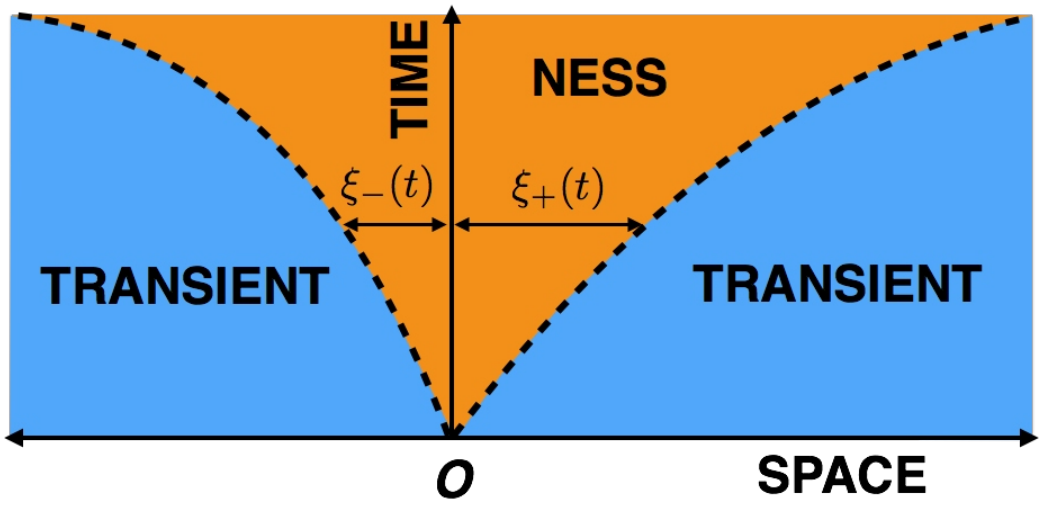


Fig.3: Non-equilibrium steady state (NESS) gets established in a core region around the resetting center O whose right and left frontiers ξ ± (t) grow with time. Outside the core region, the system is transient. [Image credit: Satya N. Majumdar, Sanjib Sabhapandit, and Gregory Schehr, (2015):Dynamical transition in the temporal relaxation of stochastic processes under resetting, Phys. Rev. E 91, 052131]

Joseph Samuel's areas of professional interests are in geometric phases, general relativity, quantum measurements and quantum entanglement. During the period 2014-2015, Samuel has pursued research on a number of themes, among which one broad theme is that of "Moving Walls and Geometric Phases" in collaboration with Paolo Facchi and Giancarlo Garnero, (INFN, Bari, Italy) and Giuseppe Marmo, (INFN, Napoli, Italy). This work is motivated by Berry and Wilkinson's early paper on diabolical points for a quantum system in a confined region whose shape can be varied. They discovered that such shape changes can lead to a change of sign of the wave function, very similar to those found in molecular physics. The work done by Samuel *et al.* treats the more general boundary conditions compatible with unitarity and scale changes. They analyze the existence of a non-trivial Berry phase associated with the dynamics of a quantum particle in a box with moving walls. They find the Berry curvature and note its connection with the Poincare metric. Moreover it has been shown that a suitable choice of boundary conditions has to be made in order to preserve unitarity. The unboundedness of the Hamiltonian describing the system is expected to naturally lead to a prescription of re-normalization for divergent contributions arising from the boundary.

A major result of the research pursued by Samuel in the past year has been in "Coarse Quantum Measurement", in collaboration with Anirudh Reddy, Kumar Shivam (PhD students, RRI) and Supurna Sinha (RRI). They present an analytical study of the Quantum Measurement Process in the context of the Stern-Gerlach experiment. Regarding the spin of a silver atom as the quantum system and its position as the measuring apparatus they have treated both the system and the measuring apparatus exactly and quantum mechanically using unitary evolution via the Schrodinger equation. They have invoked the idea that the probes that determine the position of the silver atom are limited in resolution by bounded resources. This results in 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. The coarse measurement

measurement yields information about the spin state.

This work was motivated by the desire to understand the quantum measurement process. It appears that quantum measurements involve collapse and non-unitary evolution, a process not captured by the Schrodinger equation. The explanation put forth is that it is the coarseness of the detection that leads to this apparent non-unitarity.

The final theme of Samuel's research during the previous year has been in understanding Wick rotation in tangent space. Motivated by the fact that Euclidean methods successfully reproduce entropy and temperature of black holes, which were derived by completely different methods, he has arrived at real Euclidean metrics, while maintaining the successes of the Wick rotation procedure by simply rotating the time direction. This result has been derived despite the fact that standard Wick rotation rotates the time coordinate, which in some cases leads to complex metrics.

In this work Samuel has explored a local notion of Wick Rotation in each tangent space. The idea of trivial holonomy is used to impose the condition of zero angle deficit. This results in a formulation in which rotating black holes can also be described by a real Euclidean metric.

Supurna Sinha's areas of professional research interests cover the broad spectrum of theoretical physics, especially topics in equilibrium and non-equilibrium statistical mechanics, soft condensed matter and recently in quantum measurements, quantum limits and classical and quantum entanglement. During the year gone by Sinha has worked on "Quantum Interference Experiments: a path integral point of view" in collaboration with Rahul Sawant, Joseph Samuel, Urbasi Sinha (Raman Research Institute) and Aninda Sinha o(Center for High Energy Physics, Indian Institue of Science). In a double slit interference experiment, the wave function at the screen with both slits open is not equal to the sum of the wave functions with the slits individually open one at a time, since the three scenarios represent three different boundary conditions.

In the present study, using the Feynman path integral formalism to quantify contributions from nonclassical paths in quantum interference experiments Sinha and her collaborators have found a measurable deviation in the results from a naive application of the superposition principle. They found that contributions from such paths can be significant and the publication on this work proposes simple three-slit interference experiments to directly confirm their existence.

In collaboration with Joseph Samuel, (RRI), Sinha has also explored the quantum limit on time measurement in a gravitational field. Accurate clocks are of importance both to fundamental physics and for applications in astronomy, metrology and global positioning systems. It is natural to ask if there are fundamental limits to measurement of time. In this important work Sinha has pointed out that gravity and quantum mechanics set a fundamental limit on the measurement of time. This limit arises from a combination of the uncertainty relation, the gravitational redshift and the relativistic time dilation effect.

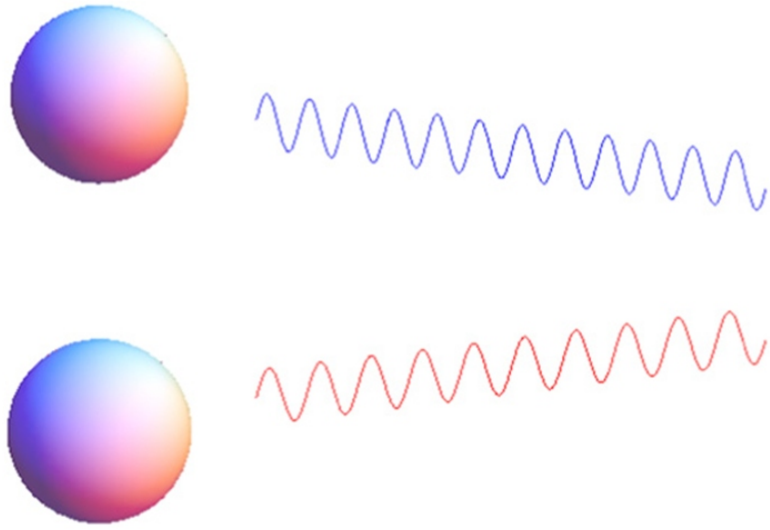


Figure 1. Atomic clock in a gravitational field g. Figure shows an atom in a trap emitting from two positions differing in height. The signal received from the lower position appears red shifted relative to the higher position. The two positions shown are within the quantum uncertainty in vertical positions of the clock. [Image Credit: Supurna Sinha and Joseph Samuel, (2015): Quantum limit on time measurement in a gravitational field, Class. Quantum Grav. 32, 015018 (7pp)]

Sumati Surya's reseach interests lie in classical and quantum aspects of gravity. The main focus of her research in the year gone by has been geared towards a number of projects among which an important one was exploring homogeneity in Quantum Gravity using the Hawking-Hartle Wave function in 2D Causal set Quantum Gravity. She has collaborated with Lisa Glaser, (Neils Bohr Institute, Copenhagen, University of Nottingham, UK) in this work. They have defined the Hartle-Hawking no-boundary wave function for causal set theory (CST) over the discrete analogs of space like hyper surfaces. Using Markov Chain Monte Carlo and numerical integration methods they then analyse the wave function in non-perturbative 2d CST. In the low temperature regime the wave function was found to be dominated by causal sets, which have no continuum counterparts. These causal sets exhibit a rapid spatial expansion with respect to the proper time and are spatially homogeneous. The results provide new insights into the possible role of quantum gravity in the observable universe.

Another project for Surya during the past year has been that of Posets with up to 76 Elements. Collaborating with Joe Henson(Imperial College), David Rideout (UCSD, San Diego) and Rafael Sorkin (Perimeter Institute), Surya has described a Markov-Chain-Monte-Carlo algorithm, which can be used to generate naturally labelled n-element posets at random with a probability distribution of one's choice. Implementing this algorithm for the uniform distribution, they have explored the approach to the asymptotic regime in which almost every poset takes on the three-layer structure described by Kleitman and Rothschild (KR). By tracking the n-dependence of several order-invariants, among them the height of the poset, they observe an oscillatory behaviour, which is very unlike a monotonic approach to the KR regime. Only around n = 40 or so does this "finite size dance" appear to give way to a gradual crossover to asymptopia which lasts until n = 82, the largest n they simulated.

The third major question tackled by Surya during the previous year was that of

Gibbons Hawking Boundary Terms for a Causal Set, a work in which she collaborated Michel Buck, Fay Dowker and Ian Jubb (Imperial College, London). In this work they have proposed a family of boundary terms for the action of a causal set with a space-like boundary. They show that in the continuum limit one recovers the Gibbons-Hawking-York boundary term in the mean.

Madhavan Varadarajan's research interests lie mainly in classical and quantum gravity. In the past year, his work with collaborator Miguel Campiglia (Postdoctoral fellow, RRI) has resulted in two major papers centred on a new representation for quantum gravity introduced by Koslowski and Sahlmann.

The Koslowski-Sahlmann (KS) representation is a generalization of the representation under lying the discrete spatial geometry of Loop Quantum Gravity (LQG), to accommodate states labelled by smooth spatial geometries.

As shown by Varadarajan in 2013, the KS representation supports, in addition to the action of the holonomy and flux operators, the action of operators which are the quantum counterparts of certain connection dependent functions known as ``background exponentials".

In the first paper with Campiglia, "The Koslowski-Sahlmann Representation: Quantum Configuration Space" (Class.Quant.Grav. 31 (2014) 175009) Varadarajan has shown that the KS representation displays the following properties, which are the exact counterparts of LQG ones:

(i) The abelian * algebra of SU(2) holonomies and 'U(1)' background exponentials can be completed to a C* algebra.

(ii) The space of semi-analytic SU(2) connections is topologically dense in the spectrum of this algebra.

(iii) There exists a measure on this spectrum for which the KS Hilbert space is realised as the space of square integrable functions on the spectrum.

(iv) The spectrum admits a characterization as a projective limit of finite numbers of copies of SU(2) and U(1).

(v) The algebra underlying the KS representation is constructed from cylindrical functions and their derivations in exactly the same way as the LQG (holonomy-flux) algebra. The only additional feature here is that the KS cylindrical functions depend on the holonomies and the background exponentials, the extra dependence being responsible for differences between the KS and the LQG algebras. While these results are obtained for compact spaces, they are expected to be of use for the construction of the KS representation in the asymptotically flat case.

The second paper by Varadarajan (again with collaborator Campiglia) during the year gone by has been the construction of a quantum kinematics for asymptotically flat space-times based on the Koslowski-Sahlmann (KS) representation. The KS representation as mentioned above is a generalization of the representation underlying Loop Quantum Gravity (LQG) which supports, in addition to the usual LQG operators, the action of `background exponential operators' which are connection dependent operators labelled by `background' SU(2) electric fields. KS states have, in addition to the LQG state label corresponding to 1 dimensional excitations of the triad, a label corresponding to a `background' electric field, which describes 3 dimensional excitations of the triad. Asymptotic behaviour in quantum theory is controlled through asymptotic

conditions on the background electric fields, which label the states, and the background electric fields, which label the operators. Asymptotic conditions on the triad are imposed as conditions on the background electric field state label while confining the LQG spin net graph labels the compact sets. Varadarajan and Campiglia have shown that KS states can be realised as wave functions on a quantum configuration space of generalized connections and that the asymptotic behaviour of each such generalized connection is determined by that of the background electric fields, which label the background exponential operators. Similar to the spatially compact case, the Gauss Law and diffeomorphism constraints are then imposed through Group Averaging techniques to obtain a large sector of gauge invariant states. It is shown that this sector supports a unitary action of the group of asymptotic rotations and translations and that, as anticipated by Friedman and Sorkin, for appropriate spatial topology, this sector contains states that display fermionic behaviour under 2 rotations. This work has also been submitted for publication.

Facilities

Research Facilities at RRI comprises of five sections – Electronics Laboratories, Soft Condensed Matter Group Labs, Mechanical Engineering Section, Library and Computer Section. These are aimed at providing specialized services to the various research projects undertaken in the institute.

Radio Astronomy Laboratory

RAL or the Radio Astronomy Laboratory has skilled electronics engineers, who are capable of conceptualizing, designing, developing and testing complex circuits, customized for special research requirements. One of the major activities of RAL 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, broadband 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.

RAL 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, modern CAD design packages for the development of FPGA systems. RAL is also fully equipped for the development and testing of x-ray astronomical 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 projects that RAL has contributed to in the past year are:

- APSERa
- Brain Computer Interface
- Bio-Physics
- LAMP projects
- Strategic Developments
- STEP-15 metre
- X-ray Polarimeter
- Engineering Developments

APSERa

Ravi Subrahmanyan, Udaya Shankar N.,Mayuri S. Rao, Raghunathan A., Somashekar R., Srivani K.S., Girish B.S and PhD and Visiting students.

The Array of Precision Spectrometers for the Epoch of Recombination- APSERa – is a 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 APSERa, wide band antennas, front-end receivers and Fast Fourier Transform (FFT) based precision Spectrometer (pSPEC) to sample and process analog signals of bandwidth of about 2 GHz are being developed.

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 socially relevant project aims at helping the physically impaired by developing devices that can be operated by our brain signals (EEG). A miniaturised versatile Voice Activated Control Unit (VACU) has been

developed that can be used to control devices by voice command. It has an on-board computer and runs from battery providing a portable unit that may be easily configured to work with a variety of systems like motors for wheel chair, electronic gadgets, etc.

A complete SSVEP based BCI system has been developed in-house that includes EEG electrodes, bio-amplifier, digitizer, signal processor and device driver. This has been used to record EEG, extract the SSVEP signal and drive external devices conditioned on the frequency detected. This system is now being miniaturised and optimized.

Biophysics

Pramod Pullarkat, Rishin P.V., Gopala Krishna M.R., Duraichelvan R., Mohammed Ibrahim, Rajagopala G., Narayanaswamy, Sushil Dubey.

The particular project for the Biophysics Lab that was taken up by the RAL over the year gone by was the development of an Axon Puller stage. The project involved designing and development of a ultra-slow motion stage that moves at the speed of a few nanometers per second, to be used in biophysics experiments that require controlled stretching of axons. During the past academic year, mechanical components were prototyped and partially fabricated. The stage has been assembled and optimised, and then interfaced to a stepper motor drive. The unit has been tested for ultra-slow movement, measured initially by linear encoder and subsequently by optical means under a microscope.

LAMP

(i) Slit based interference experiments:
Urbasi Sinha, Somsekhar

Using macroscopic architecture and a microwave source, slit-based interference experiments is being performed to detect the presence of non-classical paths. Support in the microwave aspects, like identification of a location with minimum reflection, formulation of the test-setup and installation of the transmitting and receiving horn antennae are being provided by RAL.

(ii) Development of a High Q resonant cavity to demonstrate Electromagnetically Induced Transparency Effect:
Andal Narayanan, Raghunathan A.

Electromagnetically Induced Transparency (EIT) is a technique used to significantly modify the optical response of an atomic medium. It is a quantum interference effect permitting the propagation of light through a medium, which is otherwise opaque to it under normal circumstances. This involves two fields corresponding to two transitional frequencies of a three state system. The interaction between these two fields mediated by the atomic medium is understood to be the cause for the EIT phenomenon. To facilitate this, the group has built a high – Q cavity in the radio astronomy laboratory to resonate at 3.035732 GHz. The structure has been optimized in WIPL-D, which is an electromagnetic simulation software for three dimensional objects, for maximum quality factor by shifting all the degenerate modes away from the resonant frequency. The cavity is being characterized at present for its electrical performance. Preliminary results obtained indicate that the unloaded quality factor is in the range 10,000 to 14000. Further, loading effect of the atomic samples inside the cavity on cavity performance is being investigated.

Strategic Developments

Avinash A. Deshpande, Vinutha C. Mamatha T.S., Sandhya P., Raghavendra Rao K.B., Nagaraja H.N., Prabu T., Srivani K.S., Kamini P.A., Madhavi S and Visiting students

(i) Use of the GBT-RRI MBR system back-end for SWAN:

GBT-RRI MBR is a self-contained receiver system, consisting of a dual-polarization feed covering a wide span in its spectral response (100-1500 MHz), designed for use at the prime focus of the GBT. The complete system was commissioned at Green Bank, WV, USA, during 2009, and was used successfully for tomographic study of pulsar emission cones, with the GBT. Noting the developments at Green-Bank, and the receiver needs for the next project, SWAN, this complete back-end system is proposed to be used for the phase-0 of the SWAN, along with 8 MWA tiles. For this purpose the system was shipped from Green Bank, USA to RRI. The receivers were unpacked and checked for working and housed in 10 individual 6U sub racks now, which would cater to 10 different stations for further observations.

(ii) Miniature Dual Receiver:

Development of the Analog dual miniature receiver (with IF at 140 MHz and bandwidth 16 MHz) continued through the previous year. The variable attenuator and the local oscillator are now being controlled through the USB port. The Digital receiver comprises of a low-power, 8-bit dual-channel ADC (AD9288) capable of providing a sampling rate of 100 mega samples per second. The dual channel 8-bit samples along with strobe are time multiplexed and passed to the AgFo board consisting of a Virtex-5 FPGA. The 8-bit parallel input stream at the rate of about 66 mega-samples per second, representing multiplexed raw voltage samples from the two orthogonal polarization channels, is received and after appropriate packetization the data is transmitted to the PC on a Gigabit Etherbbnet (GbE) channel, following similar formatting as in GBT-RRI MBR. The FPGA firmware for this purpose has been developed in VHDL. Any change made in the system settings are reflected instantaneously in the headers associated with the acquired data.

(iii) 16-bit ADC (AD 9650) evaluation:

The AD9650 is a dual, 16-bit, 105 MSPS analog-to-digital converter (ADC) designed for digitizing wide band, high dynamic range signals with input frequencies of up to 300 MHz. The ADC output data can be routed directly to the two external 16-bit output ports or multiplexed on a single 16-bit bus. These outputs can be set to either 1.8 V CMOS or LVDS. Programming and control of the AD9650 are accomplished using a 3-wire, SPI-compatible serial interface. Now, evaluation of the ADC board requires a Data capture board. HSC-ADC-EVALCZ-FPGA-based data capture kit (borrowed from IIA) was used to evaluate this new ADC board. The Visual Analog software was used to capture the data from the ADC. A known single tone frequency of 10.625 MHz with sampling frequency of 80 MHz was fed as the input to the ADC channels and the raw data was analysed using Matlab. It was estimated that the ADC SNR is 68 dBFS and ENOB is found to be 11 bits.

Further to replace the commercial FPGA board with a previously designed Virtex-5 FPGA board (Agfo board designed for MWA project), an interface card was designed to match the inputs and outputs of the ADC and FPGA board. A VHDL firmware is being developed to acquire the ADC data for analysis.

(iv) Rotman lens at lower frequencies:

Encouraged by the performance of a prototype Rotman lens operating at 12 GHz, a lower frequency version of such a lens (at sub-GHz frequencies) was designed and fabricated. This lens is of significantly larger physical size, and is being tested for its EM performance.

(v) Phased Array mode for MWA:

A recently concluded project at RAL was the development of digital receivers for the **Murchison Wide-field Array** (MWA). RRI had, a few years ago, entered into the MWA partnership assuming the responsibility for the design and building of the digital receivers for the 2048 dual-polarization wideband 'bow-tie' antennas operating in the frequency range 80–330 MHz, spread over a 3 km area, located in Murchison shire, Australia. RRI had successfully deployed the digital receivers during the period of the last review. The MWA has now been in successful operation in the scientific mode for the past two years – a fact that speaks volumes for the quality, reliability and ruggedness of the electronics systems designed, built, optimized and deployed by RRI. UdayaShankar N., Anish Roshi D., Avinash A. Deshpande had led the RRI effort, and key RAL participants have been Prabu T., Srivani K.S., Kamini P.A., Madhavi S., Gopala Krishna M.R.

Currently the RAL is involved in executing a full-band voltage beam-forming mode for the Murchison Wide-field Array Digital Receiver. The digital receiver has been designed to process signal from eight MWA tiles for a band between 80 and 300 MHz. The digitized outputs are processed in the digital receiver using a polyphase filter bank to get 1.28 MHz wide sub-bands. During a normal operation, 24 such sub-bands (corresponding to a 30.72 MHz band) are selected and sent out for processing in an FX correlator. To facilitate more sensitive targeted searches and fast transient observations with the MWA, the digital receiver is being enhanced to have a new mode, where a voltage beam is formed across the 80 to 300 MHz band. The digital receiver's data path and the firmware logic are enhanced to achieve this mode. The enhanced digital receiver can phase the full-band signals from eight tiles to form the voltage beams at each station. At present, the development of this beam former mode to the MWA digital receiver stands completed, and the new functionality is being tested in the lab.

15 metre STEP

B. Ramesh, Mamatha T.S., Kasturi S., Arasi Sathyamurthy, K.B.Raghavendra Rao and Visiting Students

Under this project during 2014-2015 RAL has been mainly involved in the development of the Ku-band receiver. Most parts of the Ku-band receiver have been designed and tested for satisfactory performance. Some efforts towards miniaturising and combining components to make the receiver more compact were undertaken with partial success. The ultra low-noise development, undertaken with Visiting students, also needs further work to reach completion along with the USB-digitiser. The ultimate goal is to integrate the various components into a full-fledged receiver and test it as a whole.

X-ray Polarimeter Project

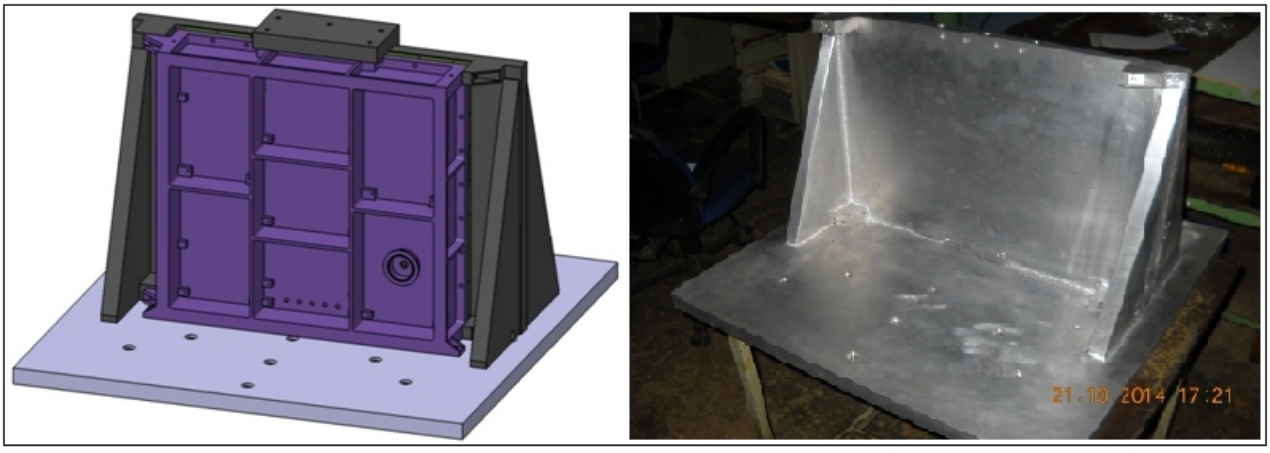
Biswajit Paul, Rishin P.V., Gopala Krishna M.R., Duraichelvan R., Chandreyee Maitra, Rajagopala G., Sandhya P., Mamatha T.S., Arasi Sathyamurthy, Nagaraja H.N. and visiting students.

There are two X-ray Polarimeter development related activities currently going on at RAL X-ray lab. These are

(a) X-ray Polarimeter - POLIX and
(b) Photo-electron Polarimeter

(a) X-ray Polarimeter - POLIX
This is an instrument designed for the energy band of 5-30keV, which works on the principle of Thomson scattering. The instrument is meant to be a payload for a small satellite astronomy mission of ISRO.

The mechanical configuration of the polarimeter consists of X-ray detectors, placed on four 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 mechanical fabrication of two more detector wire frames were taken up during this period. For the vibration test of the detectors and the wire frames, a test jig has been fabricated, so as to hold the detector on the vibration table.

In order to establish the procedure for collimator calibration, the angular response of a laboratory unit of the collimator with tapered hole has been tested. It has been found to have the required flat top response to mitigate any pointing offset of the satellite. For calibration of the engineering model collimator, a calibration jig has been designed, which will facilitate scanning of the collimator in front of an X-ray source at different angles.

On the electronics front, conversion of lab model version to pre-engineering model version of the Processing electronics (PE) cards was taken up. This involves migration from bread boarded laboratory unit towards an integrated system. Regarding the front-end electronics (FE), the engineering model is completed and the way forward is to go for space qualification tests. Space qualified layouts for the different cards have been made for this purpose. The house keeping electronics (HK)acquires and monitors important payload parameters, packetizes it and sends them to the tele-command system.

For the HK, a lab model has been developed during this period. The system has a provision for acquiring 32 analog monitoring channels whose gain can be set by a programmable gain amplifier (PGA). The channels are digitized through a 12-bit ADC and acquired currently in a PC.

The polarization measurements with POLIX requires time stamp of every photon. A time base generator of 48-bit width has been developed and tested with a local oscillator, against absolute time obtained from a GPS and checked for stability over extended period of time. This time base generator, when used in conjunction with the temperature compensated oscillator, is expected to give the required timing stability for POLIX.

The team working on this project comprises of Biswajit Paul, Rishin P.V., Gopala Krishna M.R., Varun B., Duraichelvan R., Mohammed Ibrahim, Rajagopala G., Sandhya P Mamatha T.S., Arasi Sathyamurthy,Nagaraja H.N.

(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 photoelectron is ejected in a gas, is sensitive to the polarisation of the photon, which caused it.

For the photoelectron polarimeter, the new PCB based detector wire frame designed last year with inter-wire distance of 3.2mm was tested at different pressure levels.



The unit gives results, similar to KEL-F based wireframes developed earlier; thereby opening up the possibility of using PCB based wire-frames to reduce the inter-wire separation. The long-term stability of this detector has also been established. The layout design of detector PCBs with reduced inter-wire distance of 2.4mm and 1.6mm has currently been taken up.

The team working on this project comprises of Biswajit Paul, Rishin P.V., Gopala Krishna M.R., Varun B., Duraichelvan R., Mohammed Ibrahim, Rajagopala G., Sandhya P., Nagaraja H.N., Achan Kunju

Engineering Developments:

Supravika Hegde M.R, A.Raghunathan, N. Udaya Shankar

Development of planar fat sinusoidal tooth structure:

21cm line of neutral hydrogen is considered as an unique tool to detect signals from the Epoch of reionization (EoR). The group has designed and developed a planar fat sinusoidal tooth structure, which can be used for the precise measurement of this signal. It is an all-sky feature visible at red shifted 21cm line and is predicted to be at maximum 20-30 mK. Detecting such a weak signal in the presence of the dominant Galactic and Extra-galactic background is challenging. Its precise measurement requires a detecting device such as an antenna to have frequency independent radiation pattern and return loss characteristics. Any frequency dependence results in undesired spectral features in the measured spectrum resembling the EoR signal.

The team has conducted extensive electromagnetic simulation and has shown that an antenna having a sinusoidally profiled structure exhibits both frequency

independent radiation and impedance characteristics. To achieve both these characteristics over a large bandwidth, dipoles are made generally very fat. However, with that arrangement, it is difficult to design the antenna, which can respond to two orthogonal polarizations simultaneously. To achieve this specifically, along with frequency independent radiation and smooth impedance characteristics over a large bandwidth, a planar fat sinusoidal tooth structure has been designed to operate in the frequency range 100 – 1000 MHz. Simulation results with the optimized structure indicate that

i) The return loss could be free from resonating notches over as large as 1:3 bandwidth and
ii) 10dB beamwidth could be uniform across the bandwidth with a maximum deviation of about 10 -15 %.

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, 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, thermo gravimetric analyser, infrared and UV-visible spectrophotometer, micro-balance.

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 spectrometerand 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.

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 light scattering 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 electro-acoustic spectrometer, 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 temperature range 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, bio-safety cabinet for growing cells, incubators, centrifuge and a 3D microscope for dissections. Apart from these there are ultra-sensitive force measurement setups like laser based Optical Tweezers and a home-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. We aim 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 bio-clean 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 tunnelling 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 identify molecular structures using ^{1}H and ^{13}C NMR chemical shifts. Water molecule association with the nanostructures 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 different temperatures from -180°C to 300°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. A home 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

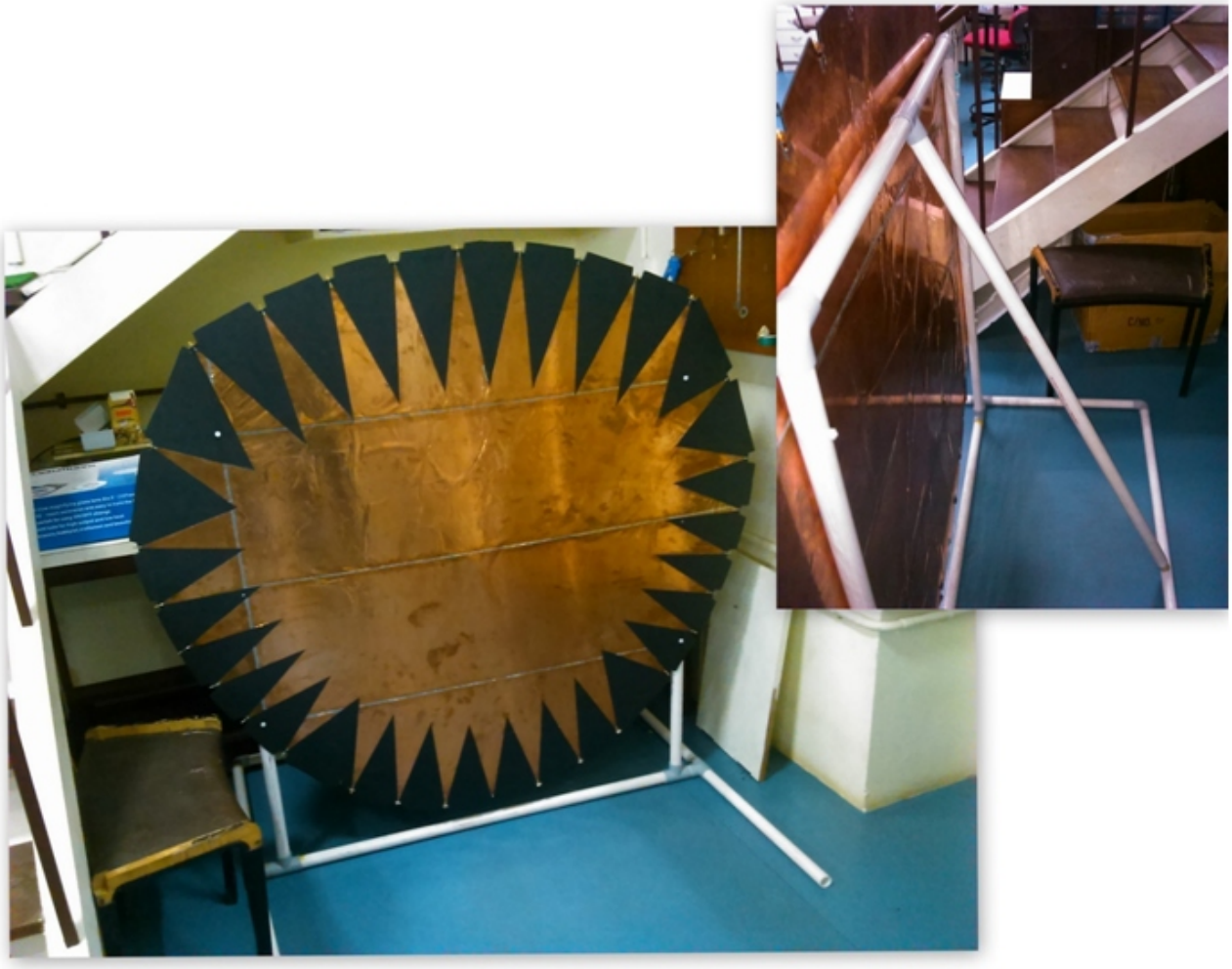
The Photophysical studies lab has two major instruments; solar simulator and photo electrochemical work station. These instruments are used to study photophysical properties of materials.

Mechanical Engineering Services (MES)

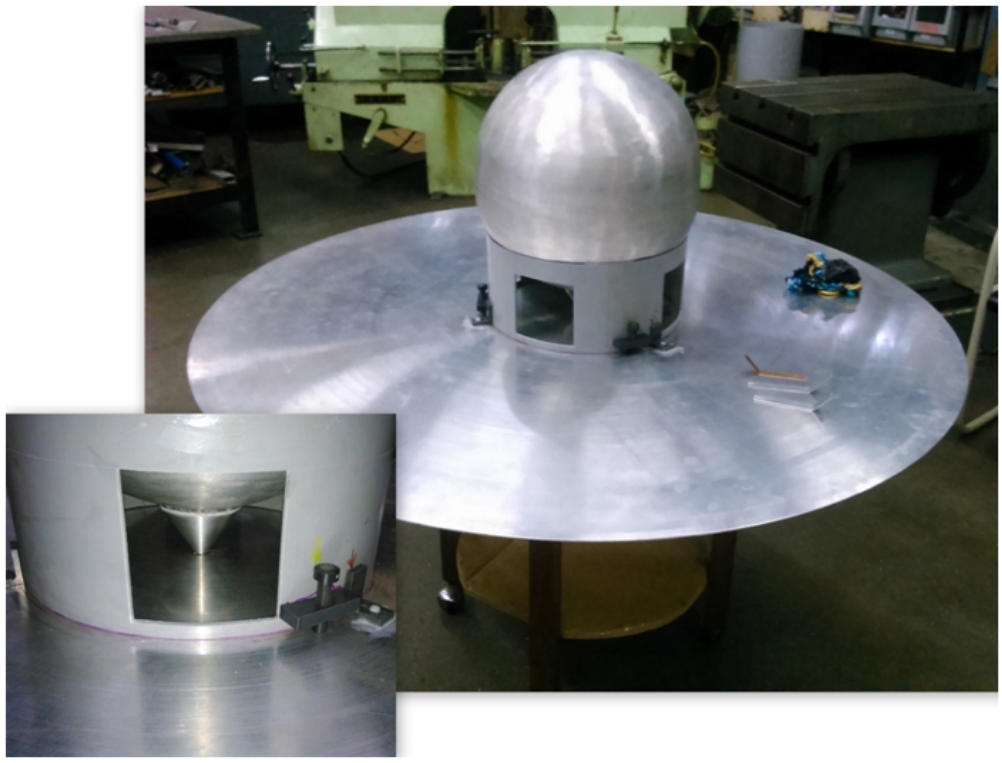
The Mechanical Engineering Services (MES) facilities at RRI consist of a machine shop and a sheet metal, paint and carpentry shop. Together they cater to the requirement of various research groups at Raman Research Institute related to Product Design, Drafting, Mechanical Engineering, Sheet metal fabrication, Carpentry, Paint works, Industrial coating, PCB engraving and Procurement. The workshop has fairly advanced machinery and a team of skilled personnel who undertake fabrication and design of various sophisticated mechanical components, enclosures, modules and racks.

Over the year gone by the major mechanical design and fabrication jobs that have been executed by the MES team for the various research labs at RRI are highlighted below:

(i) Rotman Lens - Avinash Deshpande



(ii) Spherical Monopole Antenna - A. Raghunathan



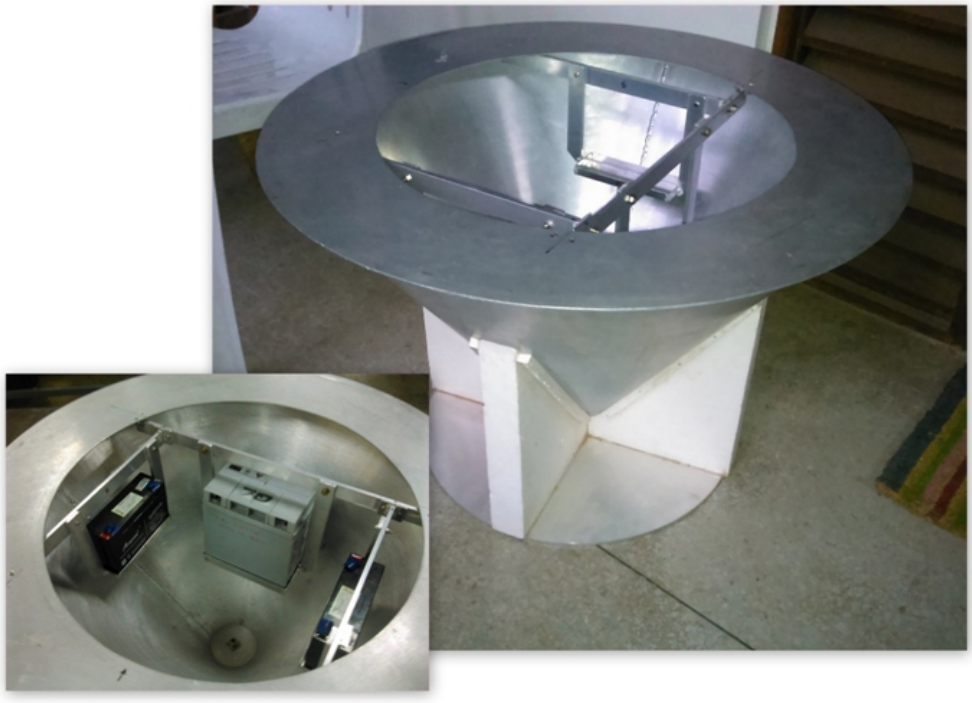
(iii) Broadband Disc Cone Antenna for RFI monitoring



Disc cone antenna Experimental set-up



iv) Low Frequency Disc Cone Antenna for EoR detection – Ravi Subrahmanyan, N. Udaya Shankar



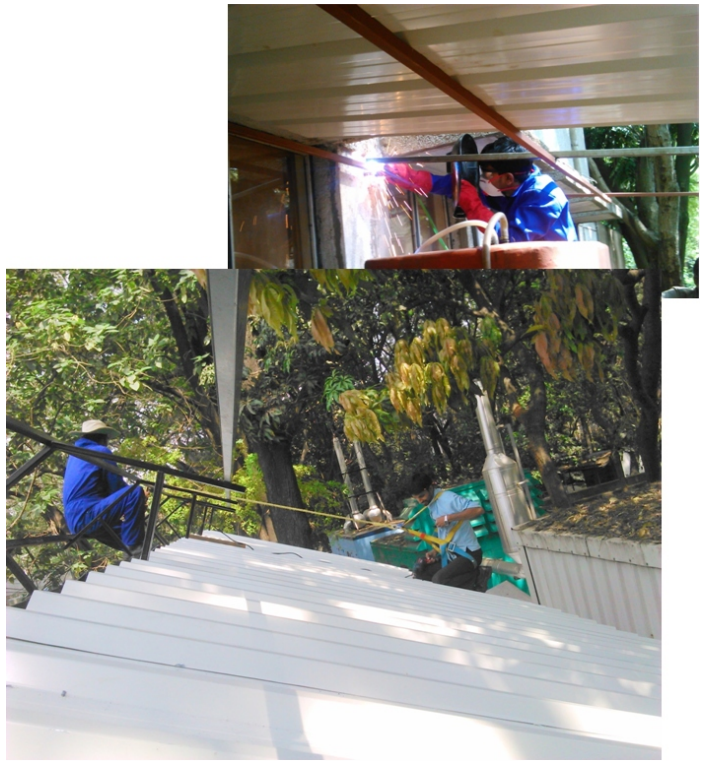
(v) SARAS digital receiver chassis – Ravi Subrahmanyan, N. Udaya Shankar



(vi) Polymer Cell Dye – Gautam Soni



(vii) Fabrication of Sheds





Library

The RRI Library founded by Sir C V Raman, started functioning with his personal collection of books and journals. The library has since then grown to become a modern library comprising of both print and electronic information resources. All the functions of the library are completely automated using LIBSYS – Library automation software. Library has been a constant source of both general and specialized information for its users. Currently, the library has a total collection of 69078 comprising of books and bound volumes of journals. This collection consists of 28372 books and 40706 Bound Volumes of journals. Library also subscribes to 94 e-journals, 54 Print and 6 Print + Online Journals. Additionally, library has in its possession 1772 non-book materials that include scientific slides, CD-ROMS, DVD's and Audio/video tapes.

In the year gone by, the library continued its partnership with the National Knowledge Resource Consortium. As a result, RRI library users have access to publications of 13 publishers amounting to 3594 journal titles. The library web page has been continuously upgraded to provide single window access to these consortium online resources.

Digital Library Activities:

Work on the digitization of archival materials, photographs and Audio/video continued during the previous year. They are being uploaded on the Institutional Repository, namely RRI Digital Repository. Current research publications, thesis submitted to RRI, photos, audio / video of events held at RRI are being added to this repository. Number of uploads has increased from 6750 to 7172 records. 200 photos of Gandhi Memorial Lectures have been added, thus increasing the total number of photos to 1400. Imprints collection section has added three profiles during this period.

RRI library supports man power development programs by giving 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 Library Science departments were trained.

Among the events organized by the RRI library during this period feature a Panel Discussion on "Books and Tablets" in association with Karnataka State Library Association to celebrate Librarians Day on 12th August 2014, Turnitin plagiarism software demonstration by Dr Ramesh Gaur, Librarian, JNU on 20th October 2014, the annual Book Exhibition on 24th and 25th November 2014, the EBSCO Discovery Services demonstration held on 16th December 2014 and finally a Panel Discussion on “Big data and eScience” held on 12th January, 2015. Organizing partners for the last event were Department of Library and Information Science, University of Mysore, MILAN – Mysore University Information and Library Science Alumni Network and Raman Research Institute.

Computer Facilities

The Computer division team handles the various computing needs of the different research and development groups and the library at Raman Research Institute.

During the year gone by the Campus network upgrade work, which was started during in 2013-2014, reached the verge of completion. The copper and fiber cable laying work has been completed. Wireless LAN controller based dual-band, 802.11 b/g/n wireless access points and edge switches with 10G uplink and 1G ports have been

deployed. The Core switch, Firewall, Network Manager, Link Load balancer have been configured and is being deployed. The new network will have 10Gbps fiber interconnect between buildings and 1Gbps Ethernet connection to desktops, campus wide wireless network with support for the latest and faster 802.11n standard. The new network will use IPv6 addressing and will work in dual-stack mode.

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

The computing facilities consist 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, 256GB RAM and 32TB storage caters to the heavy computation needs of users.

The computer facilities on campus continued to be upgraded and improved during the last year. Server Virtualization was carried out using KVM on Debian Linux(Open Source) for effective utilization of resources and minimizing the number of servers. DNS/NIS/DHCP server and the LibSys (Library management software) server were deployed as virtual servers.

Backup and storage requirements were addressed to meet increased storage needs. Operating system and hardware upgrades were undertaken for key servers, and scientific and other application packages were procured and upgraded. The group also provided and managed services like Email, web, printing, VPN and Digital Repository among others.

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 comfortably 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.

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 the 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 in 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 68 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 7 PhD degrees were awarded and 8 were submitted for review.

Postdoctoral Fellowship Programme

RRI offers a postdoctoral fellowship programme, which is open for application throughout 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 fellows 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.

Academic Programmes

Candidates who have at least one year of experience as a post doctoral researcher and have a proven track 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 6 postdoctoral and Pancharatnam fellows at RRI from the country and abroad.

Visiting Student Programme (VSP)

The Visiting Student Programme is aimed at Raman Research Institute is aimed at offering research experience to highly motivated students presently pursuing their undergraduate or master's degree. The Visiting Students Programme runs throughout the year.

During the period of their visit, these students works 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 existing graduate students at the Institute are expected to provide her/him with a flavour of the various research pursuits at RRI as well as a first-hand experience in research. This very often forms the basis of the first exposure these students have to fundamental research.

Total number of visiting students at a time was limited by available projects / mentors and relevant resources. During the year 2014-2015, a total of 150 students from different parts of the country participated in the programme, with the duration of their participation ranging anywhere between 6-weeks to 6 months (extendable up to one year). A full list of visiting students at RRI in the year 2014-2015 is given in Appendix VI.

Photo by Raju V RRI In-house on 17th April 2015

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Shiv Kumar Sethi (Coordinator)
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N Udaya Shankar
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i) Detection of epoch of reionisation (EoR),
ii) An array for the detection of epoch of recombination
iii) Instrumentation and Signal Processing for Radio Astronomy
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Lakshmi Saripalli (RRI Trust funded position)
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Nayantara Gupta
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People at RRI

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Research Interests: Dynamical systems spanning a range of scales and concerns, from instabilities in stellar black hole nuclei, to the formation and (chaotic) evolution of planetary systems, to the self-organization of swarms. He is currently working on the statistical mechanics of self-gravitating systems around super-massive black holes. In particular, he is collaborating with S. Sridhar (RRI) on a theory of resonant relaxation in such systems
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Mayuri S (Research Associate)
Research Interests:
I) Simulation and feasibility studies to experimentally detect spectral signatures from the epoch of recombination
ii) Application of maximally smooth fitting algorithm for foreground modelling towards the recovery of the 21-cm global epoch of reionization signal from synthetic sky spectrum
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Light and Matter Physics

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Urbasi Sinha
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Soft Condensed Matter

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KO Francis
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Gauribidanur Telescope

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PhD Students

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Sandeep Kr. Kataria (JAP) (from 1.9.2014)

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Sumanth Kumar (from 30.6.2014)

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Surya Narayan Sahoo (from 2.7.2014)

Ajay Kumar (from 2.7.2014)

Ayyappan J (from 7.7.2014)

Sreyas P Dinesh (from 11.7.2014)

Gaurav Tiwari (from 10.7.2014)

Soft Condensed Matter

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Ashwathanarayana Gowda
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Advisor: Sandeep Kumar

Sreeja Sasidharan
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Advisor: V.A.Raghunathan

Anindya Chowdhury (from 14.7.2014)

Theoretical Physics

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Advisor: Abhishek Dhar

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Advisor: Sanjib Sabhapandit

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Syed Nomaan Ahmed (from 8.7.2014)

D. Abhishek (from 1.7.2014)

Alkesh Yadav
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Advisor: Madan Rao

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Subrahmanya CR
Jihad R Touma

Theoretical Physics

Abhishek Dhar

Adjunct Professors

Muthukumar M

Council

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Prof. Ashutosh Singh	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	Physical & Mathematical Sciences Division Indian Institute of Science Bangalore 560012
Prof PC Agrawal	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.

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.

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R Ramesh, Internal Auditor
V Raghunath

Purchase
CN Ramamurthy, Purchase Officer
M Prema
G Gayathri

Stores
B Srinivasa Murthy, Stores Officer
MV Subramanyam

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
S Anantha Raman
K Bhoopalan
Gunashekar
C Haridas
KN Srinivas
K Palani
M Rajagopal
K G Narasimhalu
M Ramesh
A Ramanna

Security
CN Ganapathy, In-charge (consultant)
BM Basavarajaiah
UA Earappa
H Gangaiah
Keshavamurthy
Suresha
K Krishnappa
K Pushparaj
OM Ramachandra
G Ramakrishna
M Sannaiah
H Vaderappa

Consultant
S Nagaraja

Transport
MK Raju Kutty (upto 31.05.2014)
M Balarama
CK Mohanan
G Prakash
Rahamath Pasha
G Raja
M Venkateshappa

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

Horticulture
Bylappa
Lingegowda
D Mahalinga
Mailarappa
Marappa
D Muniraja
S Muniraju
Rahamathulla Khan (upto 28.2.2015)
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
Shivarudraradhya
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.

153 papers with RRI members as authors and/or co-authors were published during 2014-2015. There were 18 publications in conference proceedings and 23 publications (20 in journals and 3 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 6 book chapters and 1 book review in the past year and 2 popular science articles. 4 book chapters are still in press.

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

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, Europe, Russia, Israel, Australia, Japan, China, Korea, Singapore, Thailand, South America 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 flavour 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 complete list of speakers, their lecture topics and dates of visit to RRI is given in Appendix III.

Other Activities

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 120 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.

PhD awarded

Wasim Raja: Faraday slicing polarized radio sources

Deepak Pandey: Manipulation of Coherent Light and Coherent Light Manipulation of Atoms.

Seunghyun Lee: The study of Trapped Ion Collisions with Cold Atoms and Cold Molecules.

Pragya Srivastava: Active Mechanics of Cortical Actin: Geometry and Shape Deformation

Kanhaiya Lal Pandey: Primordial Magnetic Fields and Early Structure Formation in the Universe

Mahavir Sharma: A Study of Galactic Outflows

Anirban Polley: Molecular Organisation of Active Rafts and Phase Segregation.

PhD submitted

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 soft matter systems.

Anjan Roy: Understanding diffusion through microscopic models

Arnab Pal: Understanding fluctuations in no-equilibrium systems

Photo by Raju V RRI In-house on 17th April 2015

General

The following grants were received from the Department of Science and Technology during the year 2013-2014:

	(Amount in lakhs)
Plan (Recurring and Non Recurring)	Rs. 3140.65
Non-plan (Recurring)	Rs. 76.28
Total	Rs. 3216.93 lakhs

Journal Club

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.

The first RRI Science Forum (RSF) meeting of the year 2014 was on Astrophysical Neutrinos, the speakers being Nayantara Gupta and Jagdish Joshi. Through the year 2014-2015, 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.

Official Language Activities (2014-15)

The institute has continued to strive to achieve the targets set under the Official Language (OL) programmes by the Government of India for the year 2014-15. In compliance with these, necessary training was being provided through workshops/classes to the staff members. RRI conducted four workshops during the reporting year. It also celebrated Hindi Week in September 2014. These events were, as in the past, organized in association with Indian Academy of Sciences, which is located within the campus.

During the year, RRI could also fill up a vacated post of Junior Hindi Translator.



Reservations

The institute follows the same reservation policy as other Government of India scientific departments like the Department of Space and Department of Atomic Energy.

Others

During the period between 2014-2015, the RRI community has organized several special conferences, meetings and workshops described in detail in the next section titled 'Events organized during 2014-2015'. 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 Professor Harry Messel International Science School (ISS) has been conducted by the Science Foundation for Physics, University of Sydney, Australia, (http://www.physics.usyd.edu.au/foundation/Outreach/ISS/intro.htm), since 1962. It brings together about 140 students from around the world for two weeks of advanced study on topics of modern science. This program is conducted once every two years. Students from several countries participate in this program held every alternate year. It is scheduled to be held in Sydney, Australia during the first 2 weeks of July in 2015. The ISS offers scholarships for all the selected students and also supports the coordinators. Five scholarships are for students from India. The Raman Research Institute has been

coordinating the student selection within India since 2007. RRI has an intensive selection process to choose the five students for ISS, which includes an interview. The theme of the ISS for 2015 is *BIG - big experiments, big discoveries, big ideas*. The 2015 edition of the ISS will constitute the fifth time that Indian high school students have participated in the School.

For the year 2015 the five selected students will be spending 2 weeks at the science school where they are scheduled to listen to lectures by top international and Australian experts along with leaders from the entire breadth of science, including cosmologist Lawrence Krauss from Arizona State University, nanoscientist Michael Roukes from Caltech, and astrophysicist Naomi McClure-Griffiths from ANU. They will also be interacting with the scientists and participating in challenging science-related hands-on projects.

This apart during the period 2014-2015, a significant fraction of the RRI faculty have been engaged in public outreach activities of various kinds, details on which are as follows - Lakshmi Saripalli of RRI, part of the organizing committee for the conference on "Future of Liberal Arts in India" held in Delhi, March 18-22, 2015, delivered a talk on "Student perspectives: view from the physical sciences".

Sumati Surya gave an invited talk on "Mentoring in India" at the Indo-US workshop: Advancing Women Faculty in Science, Technology, Engineering, and Mathematics (STEM) he role of Gender in Negotiating an Academic Path" held on 15th November, Delhi. She also participated as a panelist in the "Discussion on Career Balance and Interaction with Role Models" at the International Training Programme on Leadership and Career Development for Women Scientists and Technologists 8th-12th September 2014.

V.A. Raghunathan gave a series of six introductory lectures on Soft Matter Physics to Master's level graduate students at St. Joseph's College, Bangalore.

Reji Philip has visited MVJ College, Whitefield, Bangalore, MES Degree College, Malleswaram, Bangalore, NIT Calicut as well as the Department of Optoelectronics, Kerala University, Trivandrum as an adjunct faculty under the UGC ENCORE program where he has spoken on

(i) Laser Basics
(ii) Ultrafast Lasers,
(iii) Nonlinear Optics
(iv) Nanophotonics and
(v) Laser produced Plasmas.

Madhavan Varadarajan has presented an invited talk on Quantum Gravity at St. Stephen's College, New Delhi as part of their "Feynman Club" series of lectures aimed at undergraduates.

Joseph Samuel has given a talk at the Department of Mathematics, Christ College Nov 21 2014 on "Divergent Series and applications in Physics" as part of the Science Academies' Lecture Workshop on Elementary Mathematics for First Year Undergraduate Students.

Similarly Ranjini Bandyopadhyay has taught "Soft Matter" as part of a refresher course in Physics for College Teachers at Bangalore University, Bangalore while also presenting an invited seminar titled "The curious case of Soft Matter" at the Unilever Research and Development Centre, Bangalore.

Supurna Sinha has visited the Christ University, Bangalore to deliver a one-hour lecture on "Random walks in Physics" to pre-university level students.

Besides this, many other faculty members at RRI like Biman Nath, Supurna Sinha, Joseph Samuel and others regularly publish popular science articles in journals like Resonance and Current Science meant for a more general audience. During the year gone by Biman Nath published a popular science article on "Calculus and India" in the Frontline magazine, January 7, 2015. Supurna Sinha also published an article titled "Remembering Satyendranath Bose" in the IISERTVM magazine `Sopanam 2013-2014' pg 10. Joseph Samuel contributed an article on "The Geometric Phase" in the proceedings of the one day conference on "Nine Pursuits in Science" in celebration of Prof. N. Mukunda held at IMSc, Chennai. Hema Ramachandran has contributed a book chapter on Lasing in random amplifying media to the book on Laser Physics and Technology, Springer Proceedings in Physics, 160, Chapter-8 (p 165-180), edited P.K. Gupta and R. Khare, Springer, 2015. Apart from the book chapter, she has also published a book review of the Annual Review of Cold Atoms and Molecules, edited by K.W. Madison et al, World Scientific, in Current Science, 107, 902(2014).

As a part of its public outreach activites, RRI has also donated an 8-inch Meade Optical Telescope to Dr. H.Narasimhaiah National High School, Hossur, Gauribidanur Taluq. The telescope was handed over and installed at the school on 1st February 2015 by N. Udaya Shankar. The donation was made to coincide with the Golden Jubilee celebrations of the school.



Events organized by RRI during 2014-2015

1. Bangalore School on Statistical Physics - V

This advanced level school was first started in 2010 at the Raman Research Institute, Bangalore. The first four such schools were held under the title "RRI School on Statistical Physics". The 5th school renamed as the "Bangalore School on Statistical Physics", jointly organized by RRI and the International Centre for Theoretical Sciences (ICTS) Bangalore, was held at the Raman Research Institute during March 31 – April 12, 2015.

This pedagogical school is primarily aimed at bridging the gap between Masters level courses and topics in statistical physics at the frontline of current research. It is intended for PhD students, post-doctoral fellows and interested faculty members at the college and university level.

In the 5th edition of the school, there were more than 100 selected participants from both within Bangalore and outside. Over duration of 2 weeks, the following courses were offered by instructors from both within India and abroad:

1) Introduction to fluid dynamics and turbulence – Jayanta Kumar Bhattacharjee, HRI, Allahabad

2) Quantum Dissipative Systems – Sushanta Dattagupta (Visva-Bharati, Santiniketan)

3) Statistical Field Theory – Sumit R. Das (Kentucky, USA)

4) Introduction to Stochastic Processes – Abhishek Dhar (ICTS) and Sanjib Sabhapandit (RRI)

2) Random Matrix Theory – Satya N. Majumdar (LPTMS, Orsay, France)

3) Bethe Ansatz: technique and applications – Kirone Mallick (Saclay, France)

The intensive courses consisted of 18 lectures a week, each one and a half hours long, apart from a tutorial session at the end of the day dedicated to problem solving. Some of the lectures delivered at the school have been made available online for the benefit of a wider audience. The relevant link is: https://www.icts.res.in/additional_page/641/. In addition, video recordings of the lectures are available at: https://www.icts.res.in/program/all/talks_tab/345/

2. Workshop on "Quantum Foundations and Information with a focus on the Quantum Measure and Coevent Formulation"

A workshop on "Quantum Foundations and Information with a focus on the Quantum Measure and Coevent Formulation" was

organized by Sumati Surya at the Raman Research Institute from the 5th to the 9th of January 2015. This workshop was primarily meant to be an intensive discussion meeting where a few key scientists would exchange the latest developments and ideas in the field of Quantum Measure Theory.

Several leading experts in the field like Fay Dowker, Imperial College, London, Rafael Sorkin, Perimeter Institute for Theoretical Physics, Waterloo, Canada, Joe Henson, University of Bristol, UK, David Rideout, UC San Diego, USA, Petros Wallden, University of Edinburgh, UK and Graham Brightwell from LSE, London, participated in the workshop apart from a handful of graduate students from RRI and abroad.

Through the five days of the meeting, talks of duration one and a half hours each were given followed by a focused discussion at the end of the day on related topics like Quantum Random Walk.

Local participants who spoke at the meeting included Urbasi Sinha from the Light and Matter Physics group at RRI, who delivered a talk on "Triple Slit Experiments" and Sumati Surya whose talk was titled "The extension question: where are we?" A highlight of the meeting was the talk given by Rafael Sorkin on "How interconnected is the quantum world?" He elaborated on how interpreting the path-integral as a generalized probability-measure, one is led to postulate that events of measure zero do not occur (an event being a set of histories). Because quantum amplitudes are global in nature, this type of preclusion also implies that no two parts of reality (regions of spacetime, subsystems, dots) can be fully independent which leads to an extremely interesting inseparability that loosely resembles quantum entanglement.

3. The Future of Liberal Arts and Science Education in India 2015

Built on the successes of the 2014 conference on "Wide-spectrum Education: A focus on Liberal Arts and Sciences in India" held at RRI in January, 2014, Ashoka University, O.P. Jindal Global University and Shiv Nadar University co-hosted the seconditeration of the above conference titled 'The Future of Liberal Arts and Science Education in India 2015' from March 19-21, 2015 in New Delhi. The conference, organized in collaboration with Carleton College, Yale-NUS, Claremont McKenna College, Pomona College, the Raman Research Institute and the University of Chicago Centre in New Delhi, brought together senior leaders and faculty of higher education from institutions across India and the world to discuss the challenges and opportunities for high quality teaching, scholarship and research for the Liberal Arts and Sciences in India.

While preserving the open-ended contemplation of the future of liberal arts education in India, the meeting brought together academic leaders, professors and social entrepreneurs to create new partnerships that can harness the creativity and energy of India to develop students who are capable of reinventing India's future. New forms of education being introduced in dynamic new institutions such as the ones that hosted the meeting, Ashoka University and O.P. Jindal Global University, are expected to provide a historic shift in how young people in India prepare their minds to navigate the daunting challenges that India and the world face in2015 and thereon. Newer forms of teaching, new curriculum, new types of engaged, socially relevant and interdisciplinary scholarships, were presented during the meeting in ways that

allowed for an exchange of ideas on new practices in higher education.

The three-day conference, attended by over 100 Indian and international participants, was convened in New Delhi at the Crowne Plaza Hotel in Rohini. The meeting featured day-long sessions at the campuses of the Ashoka University on March 19th and the O.P. Jindal Global University, both about an hour north of New Delhi, on March 20th. The conference gave attendees a chance to see at the ground level what the future of liberal arts education looks like – both from tours of these two new institutions, and from a rich array of presentations and conversations with leaders from across India who are helping to re-shape higher education to meet new challenges. The third day of the meeting was held at the University of Chicago New Delhi Centre, and featured talks from speakers representing a cross-section of expertise from within India and from abroad.

Some of the topics discussed were 'Cultural trends in India – reconciling traditional and modern India', 'Innovative approaches to higher education in the Humanities and Arts', 'Innovative curriculum in Social Science and Sustainability', 'Innovative pedagogy in Science and Engineering', 'How Liberal Arts can foster global connections and collaboration', 'Probable pasts and possible futures of liberal arts in India' and 'Approaches of teaching and learning in research universities in India.'

Speakers at the conference included C.Rajkumar (Vice Chancellor, Jindal Global University), Rudrangshu Mukherjee (Vice Chancellor, Ashoka University), Shiv Visvanathan (O.P Jindal University), Rupamanjari Ghosh (Director, School of Natural Sciences and Dean of Research & Graduate Studies at Shiv Nadar University), Steve Poskanzer (President, Carleton College), Bryan Penprase, (visiting professor), Yale-NUS and Chair of Physics Department, Pomona College) and also one of the organizers, Lakshmi Saripalli (Astrophysicist, Raman Trust Fellow, Raman Research Institute), Arjendu Pattanayak (Professor, Carleton College), Shailendra Raj Mehta (V-C, Ahmedabad University) and Gary Tubb (Professor in South Asian Languages at University of Chicago and Director of the University of Chicago Centre in Delhi) amongst others.

On Day three at the University of Chicago New Delhi Centre, Lakshmi Saripalli of Raman Research Institute presented a talk titled "Student Perspectives - View from the Physical Sciences".

This successful sequel to the January 2014 meeting held at RRI can be best summed up by the exploration of ways to create new forms of education within India that can enhance social justice, public service, and environmental sustainability, while also developing students to lead a new era of growth and change within India through a veritable meeting of minds between academic leaders and professors from a wide range of streams, from within India and abroad that it facilitated over the three days of the meeting.

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4. IAGRG 2015

The Indian Association for General

Relativity and Gravitation (IAGRG) holds a primarily national level meeting approximately once in two years for a period of two to three days. These meetings aim to provide a forum for the community to present their recent work as well as to promote interaction among Indian researchers in the field. The format includes keynote addresses, plenary talks, workshop sessions for presentations of contributed papers, the Vaidya-Raychaudhuri Endowment Award Lecture, the VVN Best Thesis award talks and talks by the winners of the newly constituted NR Sen Young Researcher Award. The General Body Meeting of the IAGRG also takes place at this meeting.

This year the 28th IAGRG meeting was held at Raman Research Institute during March 18th-20th, 2015. 2015 being the centenary year of Albert Einstein's presentation of the complete theory of General Relativity to the Prussian Academy, the theme of the 28th IAGRG meeting was "Celebrating the Centenary Year of General Relativity". The conference was organized jointly by RRI, IISc, Bangalore, IUCAA, Pune, IMSc, Chennai, IIA, Bangalore and SINP, Kolkata. With a little more than hundred registered participants, two keynote addresses, five plenary talks, a special session dedicated tothe GR centenary and three different workshops on "Quantum Gravity", "Cosmology" and "General Relativity and Relativistic Astrophysics" consisting of roughly twelve oral presentations and approximately ten posters, the IAGRG 2015 meeting was one of resounding success. Ramesh Narayan (Harvard University, USA) and Varun Sahni (IUCAA, Pune) delivered the keynote addresses on "General Relativity and Astrophysical Black Holes" and "Old and new ideas in Cosmology" respectively. The five plenary speakers were KG Arun (Chennai Mathematical Institute), Tarun Souradeep (IUCAA), Madhavan Varadarajan (RRI), Samir Mathur (Ohio State University, USA) and C.S. Unnikrishnan (TIFR, Mumbai).

Of special interest was the two and a half-hour long session commemorating GR centenary. Naresh Dadhich, J.V. Narlikar and C.V. Vishveshwara spoke on various topics that touched upon Indian contribution to GR research such as "GR in post-Independence India: Contributions and prospects", "The Early days of GR in India" and "Beginnings of Black Hole Physics".

The Vaidya-Raychaudhuri Endowment Award Lecture for 2015 was delivered by Bala Iyer, ICTS. His talk on "Chipping in to detect and locate the elusive gravitational wave sources: Looking back and looking forward" enlightened the audience on the still novel subject of gravitational wave detection. Archana Pai of IISER-TVM and Sandipan Sengupta of IUCAA, Pune were conferred the N.R. Sen Young Researcher Awards while Suprit Singh and Aditya Rotti, both from IUCAA were selected for the VVN Best Thesis Award. As is customary, the IAGRG General Body Meeting was also a part of the programme, where the members acknowledged the enthusiastic participation of IAGRG members and also non-members at this meeting and looked forward to the 8th ICGC (International Conference on Gravitation and Cosmology) meeting to be held at IISER, Mohali in December 2015.

The abstracts for all the talks and the poster titles can be found at http://www.rri.res.in/BookletAbstractslist.pdf while the presentations are available at the following link: http://www.rri.res.in/IAGRG2015TALKS.html in textual format. Videos of all the major presentations will be made available shortly.

5. Neighbourhood Astronomy Meeting (NAM), 2015

In June 2014 Ravi Subrahmanyan and P. Sreekumar, directors of RRI and IIA respectively, decided to revive the concept of a neighbourhood astronomy meeting in Bangalore. A core committee of Shiv Sethi and N. Udaya Shankar from RRI and Gajendra Pandey and Pravabati Chingangbam from IIA was constituted with a mandate to organize the meeting in the third quarter of 2014 itself. The committee swung into action immediately and decided to extend the invitation to participate in the Neighbourhood Astronomy Meeting to IISc, ISRO, Jawaharlal Nehru Planetarium, Bangalore and the Physics Department of Bangalore University, all of them being Astronomy and/or Astrophysics institutions or departments in Bangalore. The organizing committee was also enlarged to six with Prateek Sharma and S. Seetha from IISc and ISRO joining the organizing committee. The committee sent out invitations to all faculty members of the above institutions to actively participate in the effort to revive the Neighbourhood Astronomy Meeting. The organizers shared with them the intention to bring together colleagues working in different fields of Astronomy and Astrophysics in various institutions in Bangalore and proposed a two-day meeting with four 90-minute sessions each day. It was also agreed that an opportunity should be given to students who are in the final stages of their thesis work to present their work. The response was overwhelming and a two-day meeting was held at IIA between September 8 and 9, 2014. The last session of the reincarnated NAM was devoted to a panel discussion on deciding the future course of action on NAM meetings. The members present decided that NAM would be organized as a biannual one-day meeting with the venue moving to different participating institutions by turn. In accordance with the agreed model a second NAM was held at RRI on March 27, 2015.

The participating institutions at the March NAM, RRI, were JNP, IIA, IISc, ISRO, ICTS, RRI and BU. Four sessions of roughly two hours each were held through the day, with slots of twenty minutes each, given to twenty speakers altogether. Speakers from RRI included a few students as well as Ravi Subrahmanyan, A.A Deshpande and B. Ramesh. The topics of the talks were varied, dealing with observational astronomy, astrophysics, instrumentation and also general overviews. Some examples include "Detecting signatures of cosmological recombination and reionization in the cosmic radio background", "OH Maser Sources in W49N: Probing Differential Anisotropic Scattering with Zeeman Pairs","Telescope surface measurement using sub-aperture interferometry" and "An overview of the activities of the Jawaharlal Nehru Planetarium, Bangalore". The meeting concluded with a cultural program and dinner for all participants.

Papers in Journals

Annexure I

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Optical Materials **37**, 439-445, 2014

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101 Quantum which-way information and fringe visibility when the detector is entangled with an ancilla
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102 Effects of temperature and ground-state coherence decay on enhancement and amplification in a Delta atomic system
Manjappa, Manukumara; Undurti, Satya Sainadh; Karigowda, Asha; Narayanan, Andal; Sanders, Barry C
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117 Application of a Hough search for continuous gravitational waves on data from the fifth LIGO science run
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Aasi J*; Abbott BP*; Abbott R*; Iyer BR; +200 Co-authors
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Aasi J*; Abbott BP*; Abbott R*; Abbott T*; Iyer BR; +250 Co-authors
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121 The Koslowski-Sahlmann representation: quantum configuration space
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Physical Review D **89**, 102006, 2014

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Aasi J*; Abbott BP*; Abbott R*; Iyer BR; +250 Co-authors
Physical Review D **89**, 122003, 2014

131 Methods and results of a search for gravitational waves associated with gamma-ray bursts using the GEO 600, LIGO, and virgo detectors
Aasi J*; Abbott BP*; Abbott R*; Iyer BR; +250 Co-authors
Physical Review D **89**, 122004, 2014

132 First all-sky search for continuous gravitational waves from unknown sources in binary systems
Aasi J*; Abbott BP*; Abbott R*; Iyer BR; LIGO Scientific Collaboration; +250 Co- authors
Physical Review D **90**, 062010, 2014

133 Multimessenger search for sources of gravitational waves and high-energy neutrinos: Initial results for LIGO-Virgo and Icecube
Aartsen MG*; Ackermann M*; Iyer BR; + IceCube Collaboration; +LIGO Scientific Collaboration; +250 Co-authors
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Aasi J*; Abadie J*; Iyer BR; LIGO Scientific Collaboration; +842 Co-authors
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137 Narrow-band search of continuous gravitational-wave signals from Crab and Vela pulsars in Virgo VSR4 data
Assi J*; Abbott BO*; Iyer BR; +842 Co-authors
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Ed. J. Bicak and T. Ledvinka
Springer Proceedings in Physics **15**7, 169-175, 2014

14. Thermo-optic nonlinearity of the laser dye LDS 867 under low power CW laser excitation
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12th International Conference on Fiber Optics and Photonics, Kharagpur, India, 13-16 December 2014
Conference Proceedings from Optical Society of America, 2014, S5A.83

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Light and its interactions with Matter; AIP Conference Proceedings **1620**, 517, 2014

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   Biosensors Nanotechnology, WILEY Scrivener Publishing LLC, chapter 9, 2014

3. Liquid crystalline 1D and 2D carbon materials
   Bisoyi, Hari K; Kumar, Sandeep; Li, Quan
   Nanoscience with Liquid Crystals: From Self-Organized Nanostructures to Applications (Springer), chapter 3, 2014

4. Active Cellular Mechanics and Information Processing in the Living Cell
   Rao, Madan
   Pgs. 47-52 in Nature's Longest Threads: New frontiers in the Mathematics and Physics of Information in Biology, eds. J. Balakrishnan and B.V. Sreekantan
   World Scientific, Singapore, 2014

5. Annual Review of Cold Atoms and Molecules
   Ed. K.W. Madison et al.
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6. Consortium approach to resource sharing in an E-environment by Y.M. Patil
   Scientific Publishers, India, 2014
   Meera BM
   Book Review in Current Science 107, 308, 2014

7. Lasing in random amplifying media
   Ramachandran, Hema
   Laser Physics and Technology, Springer Proceedings in Physics, 160, Chapter-8 p 165-180, ed. P.K. Gupta and R. Khare, Springer, 2015

Popular Articles

1. Remembering Satyendranath Bose
   Sinha, Supurna
   IISERTVM magazine, Sopanam 2013-14

2. The Raman Research Institute
   Chakraborty, Debarshini
   Asia Pacific Physics Newsletter, August 2014, Vol 03, No. 02, pp 60-62

In Press

In Journals

1. Giant radio galaxies - II. Tracers of large-scale structure
   Malarecki, Jurek*; Jones, Heath*; Saripalli, Lakshmi; Staveley-Smith, Lister*; Subrahmanyan, Ravi
   Monthly Notices of the Royal Astronomical Society **449**, 955, 2015

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

3. The role of three-body H_2 formation in the fragmentation of primordial gas
   Dutta, J; Nath, Biman B; Clark PC; Klessen RS
   Monthly Notices of the Royal Astronomical Society **450**, 202, 2015

4. CMB distortion from circumgalactic gas
   Singh P; Nath Biman B; Majumdar S; Silk J
   Monthly Notices of the Royal Astronomical Society **448**, 2384, 2015

5. An analysis of the halo and relic radio emission from Abell 3376 from Murchison Widefield Array observations
   George LT; Dwarakanath KS; MWA collaborators
   Monthly Notices of the Royal Astronomical Society, 2015

6. The third post-Newtonian gravitational waveforms for compact binary systems in general orbits: instantaneous terms
   Mishra CK; Arun KG; Iyer BR
   Phys. Rev. **D91**, 084040, 2015

7. Advanced LIGO
   Iyer BR; The LIGO Scientific Collaboration
   Class. Quant. Grav, **32**, 074001, 2015

8. Tagged particle diffusion in one-dimensional systems with Hamiltonian dynamics-II
   Roy, Anjan; Dhar, Abhishek; Narayan, Onuttom; Sabhapandit, Sanjib
   J.Stat.Phys., **160**, 73-88, 2015

9. A quantum kinematics for asymptotically flat spacetimes
   Campiglia, Miguel; Varadarajan, Madhavan
   Class. Quant. Grav., **32**, 135011, 2015

10. Transbilayer lipid interactions mediate nanoclustering of lipid anchored proteins
Raghupathy, Riya; Ambika Anilkumar, Anupama; Polley, Anirban; Pal Singh, Parvinder; Yadav, Mahipal; Johnson,Charles; Suryawanshi, Sharad; Saikam, Varma; Sawant SD; Guo, Zhongwu; Vishwakarma, Ram A; Rao, Madan; Mayor, Satyajit Mayor
Cell **161**, 581-594, 2015

11. Pre-yield non-affine fluctuations and a hidden critical point in strained crystals
Das, Tamoghna; Ganguli, Saswati; Sengupta, Surajit; Rao, Madan
Scientific Reports **5**, 10644,2015

12. Optical control of resonant light transmission for an atom-cavity system
Sharma, Arijit; Ray, Tridib; Sawant, Rahul V; Sheikholeslami G; Budker D; Rangwala, Sadiq
Phys Rev. A 91, 043824, 2015

13. l-Phenylalanine functionalized silver nanoparticles: Photocatalytic and nonlinear optical applications
Nidya M; Umadevi M; Sankar P; Philip, Reji; Rajkumar BJM
Optical Materials **42**, 152, 2015

14. Size dependent nonlinear optical absorption in BaTiO3 nanoparticles
Woldu T; Raneesh B; Sreekanth P; Reddy MVR; Philip, Reji ; Kalarikkal N
Chemical Physics Letters **625**, 58, 2015

15. Quantum defect theory description of weakly bound levels and Feshbach resonances in LiRb
Pérez-Ríos, Jesús*; Dutta, Sourav ; Chen, Yong P*; Greene, Chris H*
Focus Issue: Focus on New Frontiers of Cold Molecules Research
New Journal of Physics **17**, 045021, 2015

16. Joint measurability and temporal steering
Karthik HS; Tej, Prabhu J; Devi, Usha AR; Rajagopal AK
J. Opt. Soc. Am. B 32, A34-A39, 2015

17. On the superposition principle in interference experiments
Sinha A;Vijay AH; Sinha, Urbasi
Nature Scientific Reports, 2015

18. Effects of copper nanoparticles on the thermodynamic, electrical and optical properties of a disc-shaped liquid crystalline material showing columnar phase
Yaduvanshi, Priti; Kumar, Sandeep; Dhar, Ravindra
Phase Transition **88**, 1-5, 2015

19. The influence of lateral substituents on the occurrence of a transition between two polar smectic phases with antiferroelectric properties
Radhika S; Murthy, Keshava RN; Sadashiva BK; Pratibha R
Liquid Crystals

20. Evaluation of the exfoliation and stability of Na-montmorillonite in aqueous dispersions
Ali, Samim; Bandyopadhyay, Ranjini
Applied Clay Science **114**, pp 85-92, 2015

In Conference Proceedings

1. Electro-optic and dielectric studies on quantum dot doped nematic liquid crystal
Kumar, Jitendra; Gupta RK; Kumar, Sandeep; Manjuladevi V
Macromolecular Symposia International Conference on Soft Materials- ICSM 2014; Editor: Kamlendra Awasthi

2. Productivity of Indian Telescopes: Impact Analysis through Scientometric Methods
Meera BM; Manjunath M
Astronomical Society of the Pacific Conference Series, Vol. 492, 2015

3. Enhancing access to audio and video collections of Raman Research Institute Library through digitization
Nagaraj MN; Benegal Vrinda J; Bhandi MK
ASP Conference Series **492**, 212, 2015; Edited by A.Holl et al
Proceedings of LISA VII on Open Science: At the Frontiers of Librarianship; INAF - Astronomical Observatory of Capodimonte, Naples, Italy, 17 - 20 June 2014

Book Chapters

1. Discotic liquid crystalline dimers: chemistry and applications
Setia, Shilpa; Kumar, Sandeep; Kumar Pal, Santanu
Advanced Materials Book Series, WILEY-Scrivener Publisher

2. Nanoparticles in discotic liquid crystals
Kumar, Sandeep
In "Liquid crystals with nano and microparticles", World Scientific

3. Liquid crystalline polymers derived from disc-shaped molecules in Encyclopedia of Polymers and Composites
Kumar, Sandeep, Springer

4. Discotic liquid crystalline polymers: emerging applications
Singh, Harpreet; Kumar, Sandeep; Pal, Santanu Kumar
Liquid Crystalline Polymers: Advances & Applications, Springer

* denotes co-authors who do not belong to RRI
+denotes co-authors who are Visiting Professors

CONFERENCES ATTENDED AND INSTITUTIONS VISITED

Annexure II

Name	Conferences attended / Institutions visited	Title of paper / talk
Abir Sarkar	33rd Meeting of the Astronomical Society of India National Centre for Radio Astrophysics Pune 17 – 20 February 2015	How late can the dark matter form in our universe?
	IAGRG 2015 Raman Research Institute Bengaluru 18 – 20 March 2015	How late can the dark matter form in our universe?
Andal Narayanan	University of Windsor, Canada 17 April 2014	Cavity opto-mechanical systems: A new paradigm for realizing quantum effects with light and mechanical forces
	Concordia University, Canada 5 May 2014	Cavity opto-mechanical systems: A new paradigm for realizing quantum effects with light and mechanical forces
	Discussion Meeting on Quantum Measurement Indian Institute of Science Bengaluru 22 – 24 October 2014	Weak value amplification in resonance fluorescence
Anu Renjith	International Conference on Electrochemical Science and Technology 2014 Electrochemical Society of India Bengaluru 7 – 9 August 2014	Electrochemical preparation of nanoparticle modified substrates in Deep Eutectic Solvents and their applications
Arpita Roy	1st Neighbourhood Astronomy Meeting Indian Institute of Astrophysics Bengaluru 8 – 9 September 2014	Superbubble: galactic outflows and escape of ionizing photons
	School on The Central Region of Spiral Galaxies Inter-University Centre for Astronomy & Astrophysics 12 – 23 January 2015	Superbubble: energetics, feedback to ISM, escape path for ionizing photons
Arun Roy	Indian Institute of Technology Kharagpur 9 July 2014	Phase behavior of bent-core liquid crystals
	International Conference on Frontiers in Nano Science Technology and Applications Sri Sathya Sai Institute of Higher Learning Puttaparthi 20 – 22 December 2014	Liquid crystals as soft organic nano materials (*invited*)

Ashutosh Singh	Workshop on Recent Development in Quantum Theories Banaras Hindu University Varanasi 19 – 24 February 2015	
	Conference on Young Quantum 2015 Harish-Chandra Research Institute Allahabad 24 – 26 February 2015	
Avinash Deshpande	SASTRA University Thanjavur 7 April 2014	Probing the Radio Sky : Techniques and Challenges (*KLF lecture*)
	Indian Institute of Space Science and Technology Trivandrum 16 – 17 April 2014	Fascinating Life-stories of pulsars
	India-SA Flagship Meeting Inter-University Centre for Astronomy & Astrophysics Pune 19 September 2014	Sky Watch Array Network - SWAN (*invited*)
	Arecibo Observatory Puerto Rico 7 November – 7 December 2014	OH Maser Sources in W49N: Probing Differential Anisotropic Scattering with Zeeman Pairs
	Indian Institute of Technology Kanpur 9 – 11 January 2015	Fascinating life-stories of pulsars
	Pre-ASI Workshop on Transients National Centre for Radio Astrophysics Pune 16 February 2015	Indian SWAN (Sky Watch Array Network) Initiative (*invited*)
	33rd Meeting of the Astronomical Society of India National Centre for Radio Astrophysics Pune 17 – 20 February 2015	
	Homi Bhabha Centre for Science Education Mumbai 21 February 2015	Fascinating life-stories of pulsars
	Neighbourhood Astronomy Meeting Raman Research Institute Bengaluru 27 March 2015	OH Maser Sources in W49N: Probing Differential Anisotropic Scattering with Zeeman Pairs (*invited*)

Bala Iyer	Indian Institute of Science Education and Research, Bhopal 4 – 5 April 2014	1. Relativistic gravitation: from insight to inspiration 2. LIGO-India: Locating Einstein's messengers and inaugurating gravitational wave astronomy 3. From GW detection GE astronomy
	Jawaharlal Nehru Planetarium Bengaluru 21 May 2014	1. From Newtonian gravity to general relativity 2. LIGO-India: Inaugurating gravitational wave astronomy
	KLEN College Bengaluru 26 July 2014	
	California Institute of Technology, USA 19 August 2014	The detection of gravitational waves and the two body problem in general relativity
	LIGO-Virgo Collaboration Meeting Stanford University, Stanford 25 – 28 August 2014	Report on LIGO-India (*invited*)
	Jain University, Bengaluru 13 September 2014	What is Einstein's general relativity?
	All India Science Congress 2014 Breakthrough Science Society KEB Engineers' Association Hall Bengaluru 18 October 2014	
Biman Nath	Workshop on Galaxies and Cosmology National Centre for Radio Astrophysics Pune 7 – 18 July 2014	Feedback and galaxy evolution (3 lectures)
	Gurucharan College Assam 27 December 2014	Basics of stellar structure
	Workshop on Observational and Computational Astrophysics St. Xavier's College, Kolkata 4 January 2015	Milky way: our galaxy (*invited*)
	Symposium on Structure and Evolution of Galaxies Inter-University Centre for Astronomy & Astrophysics, Pune 22 January 2015	Gaseous outflows from centres of spiral galaxies (*invited*)
	Workshop on Statistical Application to Cosmology and Astrophysics 2015 Indian Statistical Institute Kolkata 12 February 2015	Growth of structures in the universe (*invited*)

	33rd Meeting of the Astronomical Society of India National Centre for Radio Astrophysics, Pune 17 – 20 February 2015	
Biswajit Paul	40th COSPAR Scientific Assembly Lomonosov Moscow State University Moscow 2 – 10 August 2014	Timing and spectral studies of the ultra-compact binary 4U 1626-67
	Conference on X-ray polarisation in astrophysics - a window about to open? Albanova University Center Stockholm 25 – 28 August 2014	Thomson X-ray polarimeter for a small satellite mission
	1st Neighbourhood Astronomy Meeting Indian Institute of Astrophysics Bengaluru 8 – 9 September 2014	
	Indian Institute of Astrophysics Bengaluru 21 October 2014	Interplanetary space navigation with X-ray pulsars
	Workshop on Neutron Stars National Centre for Radio Astrophysics Pune 20 – 21 November 2014	Deep space navigation with X-ray pulsars
	National Centre for Radio Astrophysics Pune 24 November 2014	Birth pangs of X-ray polarimetry
	Workshop on Science with LAXPC-Astrosat TIFR Balloon Facility Hyderabad 15 - 17 December 2014	Pulse profile stability of X-ray pulsars and its applications
	Conference on Robopol and Polarimetry in Astronomy Inter-University Centre for Radio Astronomy & Astrophysics Pune 6 - 7 January 2015	POLIX: An X-ray Polarimeter
	33rd Meeting of the Astronomical Society of India National Centre for Radio Astrophysics Pune 16 – 20 February 2015	High energy counterparts of giant radio pulses
	Conference on Modern Trends in Social and Basic Sciences North Bengal University, West Bengal 27-28 March 2015	The universe as seen in X-rays
Debasish Saha	9th Annual European Rheology Conference Karlsruhe Convention Centre Germany 9 – 11 April 2014	Investigation of the dynamical slowing down process in soft glassy colloidal suspensions: comparisons with supercooled liquids

	OIST Workshop: Dynamics at Interfaces OIST Graduate University Okinawa 9 – 13 June 2014	Instabilities at interfaces between a Newtonanian fluid and an aging non-Newtonanian fluid in quasi-2D geometry
	Jawaharlal Nehru Centre for Advanced Scientific Research Bengaluru 8 – 9 August 2014 27 – 28 March 2015	Investigation of the dynamical slowing down process in soft glass colloidal suspensions: comparisons with supercooled liquids (*invited*)
Debsankar Banerjee	Institut de Biologie du Developpement de Marseille France 8 April – 14 June 2014	
Dwarakanath K.S.	Conference on Early Science from Low-frequency Radio Telescopes Arizona State University USA 8 – 12 December 2014	Cluster and supercluster observations with MWA
	33rd Meeting of the Astronomical Society of India National Centre for Radio Astrophysics Pune 16 – 20 February 2015	1. Probing cluster and super-cluster scale radio emission with the MWA 2. MWA observations of the galaxy cluster A3376
Gautam Soni	3rd International Single Molecule Biology, Genome Engineering & Genome Editing Europe – 2014 Meeting Cambridge, United Kingdom November 2014	Measuring physical properties of nucleosomes, one molecule at a time
	FCS – 2014 National Workshop on Fluorescence and Raman Techniques Indian Institute of Science Education and Research Pune 15 – 22 December 2014	Nanopore Biophysics: from gene sequencing to gene silencing (*invited*)
	Ramalingaswami Fellowship Conclave Bhubaneswar January 2015	
	IABS Conference Indian Association for the Cultivation of Science Kolkata 2 – 3 February 2015	Nanopore Biophysics: from gene sequencing to gene silencing

Gayathri Raman	Pulsar Community Meet in the SKA Workshop National Centre for Radio Astrophysics Pune 20 – 21 November 2014	SALT Observation of X-ray pulse reprocessing in 4U 1626-67
	33rd Meeting of the Astronomical Society of India National Centre for Radio Astrophysics Pune 16 – 20 February 2015	SALT Observation of X-ray pulse reprocessing in 4U 1626-67
	Neighbourhood Astronomy Meeting Raman Research Institute Bengaluru 27 March 2015	X-ray and optical orbital modulation of EXO 0748-676: A covariability study using XMM-Newton
Geetha S	Workshop on Six Sigma for LIS Professionals Raman Research Institute Bengaluru 28 June 2014	
	Indian Institute of Astrophysics Bengaluru 30 July 2014	
	Panel Discussion: Books and Tablets – Librarians' Day Raman Research Institute Bengaluru 12 August 2014	
	National Seminar on Enhancing Access to Library Resources Jain University Bengaluru 14 October 2014	
	Inauguration of National Library Week Max Mueller Bhavan Bengaluru 14 November 2014	
	Poorna Prajna Education Centre Bengaluru 17 November 2014	
	Bangalore University Bengaluru 19 November 2014	
	Seminar of Big Data and eScience Raman Research Institute Bengaluru 12 January 2015	
	Dr.S.R.Ranganathan Memorial Lectures on Digital Libraries: Redefining Boundaries and Perceptions PES University Bengaluru 3 February 2015	
Hema Ramachandran	University of Rennes 8 – 16 September 2014 19 – 25 September 2014	
	Institute of NanoSciences, Paris 18 September 2014	

	Indian Institute of Science Education and Research Kolkata 6 December 2014	
	12th International Conference on Fiber Optics and Photonics Indian Institute of Technology Kharagpur 13 – 16 December 2014	1.Tailoring photon number distributions in classical light sources (*invited*) 2.Time-delayed intensity-interferometry with light from laser-cooled atoms
Jacob Rajan	Conference on IPv6 for Enterprises Centre for Development of Advanced Computing Knowledge Park Bengaluru 8 August 2014	
Jagadeesh Rachuri	International Conference on Electrochemical Science and Technology 2014 Electrochemical Society of India Bengaluru 7 – 9 August 2014	Electrochemical studies on lipid modified film on ITO
Jagdish C Joshi	1st Neighbourhood Astronomy Meeting Indian Institute of Astrophysics Bengaluru 8 – 9 September 2014	How many of the observed neutrino events at ice cube can be described by cosmic ray interactions in the Milky Way
Joseph Samuel	University of Bologna Italy 28 April – 2 May 2014	Surface tension and the cosmological constant
	University of Naples Italy 2 – 10 May 2014	Surface tension and the cosmological constant
	University of Durham United Kingdom 10 – 17 May 2014	Surface tension and the cosmological constant
	Meeting of the Classical and Quantum Gravity Editorial Board London 30 June 2014	
	Christ College Bengaluru 21 November 2014	Divergent series and applications in Physics

Karamveer Kaur	1st Neighbourhood Astronomy Meeting Indian Institute of Astrophysics Bengaluru 8 – 9 September 2014	
	Winter School on The Central Regions of Spiral Galaxies Inter-University Centre for Astronomy and Astrophysics Pune 12 – 23 January 2015	
	Neighbourhood Astronomy Meeting Raman Research Institute Bengaluru 27 March 2015	
Kartick Chandra Sarkar	33rd Meeting of the Astronomical Society of India National Centre for Radio Astrophysics Pune 17 – 19 February 2015	Outflow from disc galaxies: effect of hot halo and rise of Fermi bubbles
	Neighbourhood Astronomy Meeting Raman Research Institute Bengaluru 27 March 2015	How do supernova driven outflows wade through the gas in the galactics halo?
Karthik HS	Indian Institute of Science Bengaluru 22 – 24 October 2014	Equivalence between joint unsharp measurements and positivity of moment matrix
	Young Quantum 2015 Harish-Chandra Research Institute Allahabad 24 – 26 February 2015	Joint measurability, steering and entropic uncertainty
Krishnamurthy S	Conference on IPv6 for Enterprises Centre for Development of Advanced Computing Knowledge Park, Bengaluru 8 August 2014	
Lakshmi Saripalli	Brandeis University, USA 22 – 30 October 2014	Giants among radio galaxies
	Australian National University Australia 13 – 23 November 2014	
	Yale-NUS Liberal Arts College Singapore 1 – 7 March 2015	1. Interconnections – an astronomer's diary 2. Radiogalaxies
	Conference on Future of Liberal Arts Crowne Plaza Hotel in Rohini New Delhi 18 – 22 March 2015	Student perspectives: view from the physical sciences

Lijo George Thomas	1st Neighbourhood Astronomy Meeting Indian Institute of Astrophysics Bengaluru 8 – 9 September 2014	
	33rd Meeting of the Astronomical Society of India National Centre for Radio Astrophysics Pune 17 – 20 February 2015	MWA observations of the galaxy cluster Abell 3376
Madan Rao	University of Aix-Marseilles Marseilles 12 May 2014	Active control of cell surface composition
	University of Aix-Marseilles Marseilles 26 May 2014	Active mechanics of information processing at the cell surface
	Gordon Research Conference on Biointerfaces Renaissance Tuscany Il Ciocco Lucca (Barga), Italy 15 – 19 June 2014	
	IUPAP International Conference on Biological Physics Institute of Physics Beijing 20 – 22 June 2014	Active mechanics of information processing and computation at the cell surface
	CSRC Workshop – Statistical Physics of Active Matter Computational Science Research Center Beijing 24 - 25 June 2014	Active mechanics of cellular computation
	Simons Monsoon School National Centre for Biological Sciences Bengaluru 21 – 26 July 2014	Soft biological matter: physics of living matter
	International Conference on Soft Materials Malaviya National Institute of Technology Jaipur 6 – 10 October 2014	Active computational fluids
	SoftComp Topical Workshop: Proteins & Nanoparticles @ Membranes Forschungszentrum Jülich Germany 19 – 22 October 2014	Active composite cell surface: active clustering and active membrane deformation
	ASCB/IFCB 2014 Meeting American Society for Cell Biology Philadelphia 6 December 2014	1. Active composite cell surface and its implications 2. Physical models for organelle biogenesis and morphology
	Indian Institute of Science Education and Research Pune 15 December 2014	Active biological matter: physics of living matter (*lecture series*)
	Prof. Sanjay K Biswas Memorial Lecture Indian Institute of Science Bengaluru 24 January 2015	Mechanics of information processing in the cell

	National Centre for Biological Sciences Bengaluru 4 – 6 February 2015	Active control of clustering and segregation at the cell surface
Madhavan Varadarajan	St. Stephen's College Delhi 26 – 30 September 2014	Quantum gravity
	Jawaharlal Nehru Centre for Advanced Scientific Research Bengaluru 21 October 2014	Quantum gravity: a view from general relativity
	IAGRG 2015 Raman Research Institute Bengaluru 18 – 20 March 2015	Canonical gravity: spacetime covariance, quantization and a new classical identity (*invited, plenary*)
Manjunath M	Workshop on Presentation Skills for Library and Information Professionals Karnataka State Library Association Bengaluru 26 – 27 September 2014	
	KanOE: Centre for Knowledge Analytics and Ontological Engineering Workshop Sarada Ranganathan Centre for Information Studies Bengaluru 3 February 2015	
Mayuri S	Australian National University Australia 26 June 2014	On the detection of spectral ripples from the epoch of recombination
	Harley Wood Winter School Sydney 17 – 20 July 2014	
	CASS Radio Astronomy School Australia Telescope Compact Array Narrabri 29 September – 3 October 2014	
	Mt. Stromlo Christmas Seminars Mt. Stromlo Observatory Australia 13 – 14 November 2014	The hidden message from the first atoms
	Early Career Researcher's Workshop University of Queensland Australia 18 November 2014	
	CAASTRO Annual Retreat 2014 ARC Centre of Excellence for All-sky Astrophysics Australia 19 – 21 November 2014	On the detection of spectral ripples from the epoch of recombination

	Neighbourhood Astronomy Meeting Raman Research Institute Bengaluru 27 March 2015	
Meena S	NI Days – Technical Seminar on LabView and Graphical System Design Nimhans Conventional Hall Bengaluru 17 September 2014	
	Avnet X-fest 2014 Avnet India Bengaluru 9 December 2014	
Meera B.M.	International Conference on Library and Information Services in Astronomy VII: Open Science at the Frontiers of Librarianship INAF-Astronomical Observatory of Capodimonte Italy 17 – 20 June 2014	Productivity of Indian Telescopes: Impact analysis through Scientometric methods
	Springer e-book summit Hilton Hotel, Goa 21 – 23 September 2014	Changing Dimensions of Librarianship and Library Services with Digital Content (*Invited*)
	Conference on Open Access SAARC CSIR – URDIP Pune 13 – 14 October 2014	Imprints collection: A value addition to open access resources of RRI
	Inauguration of National Library Week Max Mueller Bhavan Bengaluru 14 November 2014	
	PES Institute of Technology Bengaluru 4 February 2015	
Meera Thomas	1st Neighbourhood Astronomy Meeting Indian Institute of Astrophysics Bengaluru 8 – 9 September 2014	Effect of variability of X-ray binaries on X-ray luminosity functions of Milky Way
	Conference on Neutron Star Physics with the Square Kilometer Array National Centre for Radio Astrophysics Pune 20 – 21 November 2014	Orbital evolution of the eclipsing HMXB 4U 1700-37
	33rd Meeting of the Astronomical Society of India National Centre for Radio Astrophysics Pune 17 – 20 February 2015	Long term averaged and composite spectrum of X-ray binaries

Nafisa Aftab	1st Neighbourhood Astronomy Meeting Indian Institute of Astrophysics Bengaluru 8 – 9 September 2014	
	Neighbourhood Astronomy Meeting Raman Research Institute Bengaluru 27 March 2015	
Nagaraj MN	International Conference on Library and Information Services in Astronomy VII: Open Science at the Frontiers of Librarianship INAF-Astronomical Observatory of Capodimonte Italy 17 – 20 June 2014	Enhancing access to audio and video collection of Raman Research Institute Library through digitization
	Workshop on Presenting Skills Sarada Ranganathan Endowment for Library Science Bengaluru 26 – 27 September 2014	
	Interactive Library Event Hotel Le Meridien Bengaluru 21 November 2014	
	Dr.S.R.Ranganathan Memorial Lecture on Digital Libraries: Redefining Boundaries and Perceptions PES University Bengaluru 3 February 2015	
Nayantara Gupta	National Centre for Radio Astrophysics Pune 18 August 2014	Electrons, positrons and Fermi bubbles
Nazma Islam	1st Neighbourhood Astronomy Meeting Indian Institute of Astrophysics Bengaluru 8 – 9 September 2014	Effect of variability of X-ray Binaries on X-ray luminosity functions of Milky Way
	Conference on Neutron Star Physics with the Square Kilometer Array National Centre for Radio Astrophysics Pune 20 – 21 November 2014	Orbital evolution of the eclipsing HMXB 4U 1700-37
	33rd Meeting of the Astronomical Society of India National Centre for Radio Astrophysics Pune 17 – 20 February 2015	Long term averaged and composite spectrum of X-ray binaries
Pramod Pullarkat	Indian Institute of Science Bengaluru 7 August 2014	Active mechanics and shape instabilities in axons

	National Workshop on Fluorescence and Raman Techniques Indian Institute of Science Education and Research Pune 14 - 22 December 2014 October and November 2014	Rheological studies on axons using a home-developed Micro-Extension Rheometer (*invited*)
	Complex Fluids Symposium Compflu2014 Jawaharlal Nehru Centre for Advanced Scientific Research Bengaluru 22 - 24 December 2014	Rheological studies on axons using a home-developed Micro-Extension Rheometer (*invited*)
	Meeting on Interdisciplinary Approach To Biological Sciences Indian Association For the Cultivation of Science Kolkata 2 – 3 February 2015	How actin cytoskeleton couple cell spreading to nuclear geometry? (*invited*)
	Meeting on Current Trends in Condensed Matter Physics National Institute of Science Education and Research Bhubaneswar 19 - 22 February 2015	How actin cytoskeleton couple cell spreading to nuclear geometry? (*invited*)
	Workshop on Emerging Concepts of The Neuronal Cytoskeleton Hotel Patagónico Chile 22--26 March 2015	Shape dynamics and mechanical responses of axons
Prasad V.V.	Workshop on Advances in Nonequilibrium Statistica lMechanics Galileo Galilei Institute for Theoretical Physics Florence 25 May – 5 July2014	High-energy tail of the velocity distribution of driven inelastic Maxwell gases
	Statphys – Kolkata VIII S.N.Bose National Centre for Basic Sciences Kolkata 1 – 5 December 2014	Driven inelastic Maxwell gases
	Indian Statistical Physics Community Meeting Indian Institute of Science Bengaluru 13 – 15 February 2015	
Pratibha R	Institut at Jozef Stefan, Slovenia 1 – 11 April 2014	
	21st National Conference on Liquid Crystals CSJM University Kanpur 10 – 12 November 2014	Chiral segregation induced by electric fields in the dark conglomerate liquid crystal (*invited*)
Priyanka Singh	Workshop on Galaxies and Cosmology National Centre for Radio Astrophysics Pune 7 – 18 July 2014	

	Summer School on Cosmology International Centre for Theoretical Physics Trieste 4 – 15 August 2014	Secondary CMB distortion from circum-galactic medium
	1st Neighbourhood Astronomy Meeting Indian Institute of Astrophysics Bengaluru 8 – 9 September 2014	
	Tata Institute of Fundamental Research Mumbai 5 – 14 June 2014 18 – 31 December 2014	
	33rd Meeting of the Astronomical Society of India National Centre for Radio Astrophysics Pune 17 – 20 February 2015	CMB distortion circum-galactic medium from and its detectability
	Neighbourhood Astronomy Meeting Raman Research Institute Bengaluru 27 March 2015	
Raghunathan VA	Macro 2015 International Symposium on Polymer Science and Technology Kolkata 23 – 26 January 2015	Tuning the architecture of DNA-amphiphile complexes with counterions (*invited*)
Rahul Sawant	20th National Conference on Atomic Energy and Molecular Physics Indian Institute of Space Science and Technology Trivandrum 9 – 12 December 2014	Optical bistability in a system of multi-level atoms and cavity
	Weizmann Institute of Science Israel 10 – 13 March 2015	
Raj Hossein	The Indian Statistical Physics Meeting Indian Institute of Science Bengaluru 13 - 15 February 2015	Diffusion of passive particles in an active medium
Rajarshi Basak	ICTS Light-Mat 2014 Indian Association for the Cultivation of Science, Kolkata 8 – 22 December 2014	
Ranjini Bandyopadhyay	Bengaluru University, Bengaluru 2 April 2014	Soft matter (*invited*)
	9th Annual European Rheology Conference Karlsruhe Convention Centre Germany 21 – 24 May 2014	Scaling law in convection-driven Brazil nut effect (*invited*)

	Indian Institute of Science Bengaluru 7 August 2014	Experiments with rising Brazil nuts and aging colloidal suspensions (*invited*)
	Discussion Meeting on Glasses and Glass Formers Jawaharlal Nehru Centre for Advanced Scientific Research, Bengaluru 8 – 9 August 2014	
	Nagoya University, Japan 26 September 2014	The dynamical slowing down process in soft colloidal glasses of charged disks
	Complex Fluids Symposium Jawaharlal Nehru Centre for Advanced Scientific Research Bengaluru 24 December 2014	Experimental studies of the aging dynamics of colloidal clay suspensions (*invited*)
	The Indian Statistical Physics Meeting Indian Institute of Science Bengaluru 13 February 2015	Dynamics of a suspension of charged disks
	Unilever Research and Development Bengaluru 27 February 2015	The curious case of soft matter (*invited*)
Ravi Subrahmanyan	Australian National University Australia 17 March – 13 April 2014 13 – 23 November 2014	Extragalactic background light at long wavelengths: a tracer of cosmic evolution
	University of Western Australia Australia 14 – 18 April 2014	Extragalactic background light at long wavelengths: a tracer of cosmic evolution
	URSI-GA 2014 Meeting China 18 – 23 August 2014	Signatures in the cosmic radio background from spin flip and recombination in cosmological hydrogen
	Netherlands Institute for Radio Astronomy The Netherlands 8 – 10 October 2014	
	Brandies University Boston 21 – 30 October 2014	Evolution of the universe sketched in the light of the night sky
	University of Sydney Australia 13 – 23 November 2014	
Reji Philip	Conference on Recent Advances in Optical Sciences University of Hyderabad 26 - 27 April 2014	The effect of physical phenomena on optical nonlinearity in nanostructured materials (*invited*)

	National Seminar on Nanophotonics M.G. University, Kottayam 26 June 2014	Nanophotonics Technologies (*invited*)
	Faculty Development Programme National Institute of Technology Calicut 2 July 2014	Nanophotonics Technologies
	State Level Science Festival of the Breakthrough Science Society MES Degree College Bengaluru 26 July 2014	Plasmas from lasers
	National Seminar on Current Trends in Materials Science Aquinas College, Edacochin 13 - 14 August 2014	Nanophotonics (*invited*)
	The 2nd DAE-BRNS Theme meeting on Ultrafast Science Manipal University, Manipal 30 October – 1 November 2014	1. Acceleration of neutrals in an ultrafast laser produced Zn plasma (invited) 2. Spectral dispersion of ultrafast optical limiting in reduced graphene oxide
	National Seminar on Facets of Physics Providence College, Calicut 6 - 7 November 2014	Nanophotonics (*invited*)
	Swadeshi Science Congress Malayalam University Kerala 6 - 8 November 2014	Optical time of flight measurements of laser produced metal plasmas: Short-pulse and ultrafast excitations (*invited*)
	Energy Materials Nanotechnology 2014 Fall Meeting, Hilton Hotel, USA 22 – 25 November 2014	Nonlinear Optical Absorption properties of LBMO/ZnO/LAO thin films (*invited*)
	29th National Symposium on Plasma Science and Technology M.G. University, Kottayam 7 - 11 December 2014	1. Expansion dynamics of a laser produced Zn plasma: short-pulse and ultrafast excitations (*invited*) 2. Nanosecond and femtosecond laser produced aluminium Plasmas: A comparative study 3. Excitation energy dependence of dye fluorescence lifetime in the presence of metal nanoparticles

	International Conference on Frontiers in Nanoscience Technology and Applications SSSIHL Prasanthi Nilayam 20 - 22 December 2014	Ultrafast laser-induced plasmas for nanoparticle generation: comparison with conventional chemical routes *(invited, keynote)*
	MVJ College Bengaluru 27 February 2015	Lasers and their applications
	Kerala University Trivandrum 2 - 6 March 2015	1. Laser basics 2. Ultrafast Lasers 3. Nonlinear Optics 4. Nanophotonics 5. Laser produced plasmas
Rishin PV	Space Astronomy Group Indian Space Research Organisation Bengaluru 2 May 2014	X-ray Polarimeter – POLIX design and development status (*invited*)
Sadiq Rangwala	557. Wilhelm und Else Heraeus-Seminar - Trapped Ions Meet Cold Atoms Wilhelm und Else Heraeus Foundation, Germany 27 – 29 March 2014	Cavity enclosed hybrid trap for ions, atoms and molecules
	Discussion Meeting on Quantum Measurements Indian Institute of Science Bengaluru 22 – 24 October 2014	
	Indian Institute of Technology Chennai 29 October 2014	Dance of ions and atoms in a hall of mirrors
	ICTS Light-Mat 2014 Indian Association for the Cultivation of Science Kolkata 19 – 22 December 2014	Hybrid traps for ions, atoms and light for the study of interactions
	11th Asian Atomic and Molecular Physics Seminar Sendai University Japan 5 - 10 October 2014	
	Punjab University Chandigarh 25 February 2015	CHASON
	Weitzmann Institute Israel 10 – 13 March 2015	Coupled atom-cavity physics: different closed and open systems
	Workshop on Quantum Information and Quantum Dynamics in Ion Traps Carlton Hotel Israel 14 – 19 March 2015	

Samim Ali	88th ACS Colloids and Surface Science Symposium, University of Pennsylvania USA. 22 - 25 June 2014	Using ultrasound method for the evaluation of dispersibility and stability of clay colloids in aqueous suspensions
	IRTG-4th SoMaS School "Soft Materials Under External Constraints" International Research Training Group France 6 - 11 July 2014	Aqueous suspensions of charged clay minerals: dispersibility, stability and rheological response
	Georg-August-Universität Göttingen Germany 14 July 2014	Natural clay suspensions: dispersibility, stability and rheological behaviour
	Montpellier University 2 France 17 July 2014	Aqueous suspensions of charged clay minerals: dispersibility, stability and rheological response
	Liquids 2014 - 9th Liquid Matter Conference University of Lisbon, Portugal 21 - 25 July 2014	1. Linking microstructures to the bulk mechanical behaviors of colloidal gels 2. Using ultrasound method for the characterization of aqueous suspensions of clay-colloids
Sandeep Kumar	University of Allahabad Allahabad 15 April 2014 4 August 2014 22 November 2014 2 February 2015	
	Institute of Advanced Study in Science & Technology Guwahati 24 June 2014	
	National Conference on Liquid Crystals 2014 CSJM University Kanpur 8 November 2014	Discotic photovoltaics (*invited*)
	Jawaharlal Nehru University Delhi 15 December 2014	Dispersion of zero-, one- and two-dimensional nanoparticles in the supramolecular order of discotic liquid crystals
	Kyushu Institute of Technology Japan 9 January 2015	Discotic nanocomposites: a new class of organic semiconductors (*invited*)

	University of Mangalore Mangalore 13 January 2015	
	Centre for Nanoscience and Soft Matter Bengaluru 20 January 2015	Recent advances in discotic soft matters and nanoscience (*invited*)
	Conference on Recent Trends in Advanced Materials and Nanotechnology CMR Institute of Technology, Bengaluru 23 January 2015	Liquid crystalline nanocomposites as advanced materials for opto-electronics (*invited*)
	Department of Electronics and Information Technology, New Delhi 10 February 2015	
	Indian Association for the Cultivation of Science Kolkata 24 March 2015	Supramolecular nanocomposites as advanced materials for opto-electronics (*invited*)
	National Conference on Current Perspectives on Research on Chemical Sciences 2015 Assam University, Silchar 25 - 26 March 2015	Supramolecular nanocomposites as advanced materials for opto-electronics (*plenary*)
Sanjay Kumar Behera	Compflu- Eighth Symposium on Complex Fluids Jawaharlal Nehru Centre for Advanced Scientific Research Bengaluru 22 – 24 December 2014	
Sanjib Sabhapandit	Laboratoire de Physique Theorique et Modeles Statistiques France 21 April -5 May 2014 31 May – 3 June 2014	High-energy tail of the velocity distribution of driven inelastic maxwell gases
	Workshop on Advances in Nonequilibrium Statistical Mechanics: Large Deviations and Long-range Correlations, Extreme Value Statistics, Anomalous Transport and Long-range Interactions Galileo Galilei Institute for Theoretical Physics Florence 5 May – 4 July2014	High-energy tail of the velocity distribution of driven inelastic Maxwell gases(*invited*)
	Indo-British Frontiers of Science Symposium Hotel Dukes Retreat Khandala 9 - 12 October 2014	Large deviations, extreme events and search problems (*invited*)
	Statphys – Kolkata VIII S.N.Bose National Centre for Basic Sciences Kolkata 1 – 5 December 2014	Universal large deviations for the tagged particle in single file motion (*invited*)

	Indo-Israeli Meeting on Frontiers in Condensed Matter Physics Israel Academy of Sciences and Humanities Israel 8 – 11 December2014	Universal large deviations for the tagged particle in single file motion (*invited*)
	Tata Institute of Fundamental Research Mumbai 22 – 31 December 2014	Universal large deviations for the tagged particle in single file motion
	Indian Institute of Technology Mumbai 31 December 2014 – 2 January 2015	Fluctuations and large deviations in non-equilibrium systems
	Indian Statistical Physics Community Meeting Indian Institute of Science Bengaluru 13 – 15 February 2015	Universal large deviations for the tagged particle in single file motion
Saurabh Singh	33rd Meeting of the Astronomical Society of India National Centre for Radio Astrophysics Pune 17 – 20 February 2015	Precision receiver for detection of redshifted 21cm signal from the epoch of reionization
Sourabh Paul	1st Neighbourhood Astronomy Meeting Indian Institute of Astrophysics Bengaluru 8 – 9 September 2014	Study of redshifted HI from the epoch of reionization
	33rd Meeting of the Astronomical Society of India National Centre for Radio Astrophysics Pune 17 – 20 February 2015	21cm epoch of reionization and foregrounds study with Murchison Widefield Array
Srinivasa HT	Workshop on Crystallography in the sciences: a celebration of the International year of Crystallography 2014 Bengaluru University Bengaluru 16 – 17 October 2014	
	National Conference on Pure and Applied Chemistry 2014 Mysore University Mysore 29 – 31 December 2014	Heterocycles with liquid crystalline properties: synthesis and characterization of symmetrical 3,5-Pyrazoles and Isoxazoles possessing central bent-core unit
Sumati Surya	Workshop on Foundations of Quantum Mechanics and Quantum Gravity Imperial College, London 25 – 26 April 2014	Quantum measure formulation (*invited*)

	International Workshop on Relativistic Quantum Information University of Seoul, Korea 30 June – 3 July 2014	Covariance and quantum theory: a measure theoretic perspective (*invited)*
	International Training Programme on Leadership and Career Development for Women Scientists and Technologists National Institute of Advanced Studies Bengaluru 8 – 12 September 2014	
	Center for High Energy Physics Bengaluru 7, 10 November 2014	An introduction to causal set quantum gravity
	Indo-US workshop: ADVANCing Women Faculty in Science, Technology, Engineering, and Mathematics Hotel Lalit, New Delhi 15 November 2014	Mentoring in India (*invited*)
	Workshop on Quantum Foundations and Information with a focus on the Quantum Measure and Coevent Formulation Raman Research Institute Bengaluru 5 – 9 January 2015	The Extension Question: Where are we?
	Chennai Mathematical Institute Chennai 23 February 2015	The Gibbons-Hawking-York Boundary Term in a Causal Set
	IAGRG 2015 Raman Research Institute Bengaluru 18 – 20 March 2015	
Supurna Sinha	University of Bologna, Italy 28 April – 2 May 2014	Statistical mechanics of semiflexible ribbons
	University of Naples, Italy 2 – 10 May 2014	Statistical mechanics of semiflexible ribbons
	University of Durham United Kingdom 10 – 17 May 2014	Entanglement control via geometric phase
	Discussion Meeting on Quantum Measurement Indian Institute of Science Bengaluru 22 – 24 October 2014	
	Christ University, Bengaluru 10 January 2015	Random walks in Physics
Sushil Dubey	Bengaluru Microscopy Course 2014 National Centre for Biological Sciences Bengaluru 21 – 28 September 2014	Active and passive responses of axonal cytoskeleton

	Conference on Interdisciplinary Approach to Biological Sciences Indian Association for the Cultivation of Science Kolkata 2 – 3 February 2015	Active and passive responses of axonal cytoskeleton
Udaya Shankar	Third Workshop for Pulsar Observatory for Students Radio Astronomy Centre, Ooty 14 – 17 July 2014	Fundamental of synthesis imaging telescopes
	URSI-GA 2014 Meeting China 16 – 23 August 2014	Antennas, space beam splitters and receivers for precision radiometers exploring the reionization and recombination epochs
	International School for Young Astronomers National Astronomical Research Institute of Thailand, Thailand 14 November – 12 December 2014	Radio astronomy: past, present and future (3 talks)
	Conference on Early Science from Low-frequency Radio Telescopes Arizona State University USA 8 – 10 December 2014	1. A new generation digital receiver for The Murchison Wide field Array 2. Software correlator 3. Study of the 21 cm epoch of reionization and foregrounds with Murchison Widefield Array 4. A dual role for MWA in the detection of signals from EoR
	Interactive Workshop on Thrust Areas in Radio Astronomy Lady Doak College, Madurai 2 March 2015	
Urbasi Sinha	Nicolas Copernicus University Poland 12 November 2014	Non classical paths in quantum interference experiments
	ICTS Discussion Meeting on Light-Matter Interactions Indian Association for the Cultivation of Science Kolkata 19 – 22 December 2014	Three slit experiments
	IEEE Photonics Society Workshop on Quantum Computation and Quantum Communication Indian Institute of Science Bengaluru 8 January 2015	Quantum experiments: entanglement, computation and interference

	Discussion Meeting on Quantum Measure Theory Raman Research Institute Bengaluru 5 – 9 January 2015	Quantum experiments: entanglement, computation and interference
Yashodhan Hatwalne	University of Durham United Kingdom 18 June – 17 August 2014	

COLLOQUIA AND SEMINARS

Annexure III

Name	Title	Date
Peter Heftberger University of Graz, Austria	The evolution of a high resolution global SAXS data analysis for multilamellar lipid vesicles	9 April 2014
Benjamin Kollmitzer University of Graz, Austria	Protein partitioning in liquid-ordered (Lo) / liquid-disordered (Ld) domains depends on lipid composition and protein shape	9 April 2014
Auditya Sharma Tel Aviv University, Israel	Is the ferromagnet on a Cayley tree a closed problem?	15 April 2014
Piotr Kolenderski Nicolus Copernicus University Poland	Single photons for quantum communication	15 April 2014
Amitava Sen Gupta Council of Scientific and Industrial Research-National Physical Laboratory New Delhi	Development of atomic clocks at the CSIR – National Physical Laboratory	29 April 2014
Pallava Bagla New Delhi Television, New Delhi	How can scientists communicate better with the public? Insights and experiences of a news reporter	8 May 2014
Sushan Konar National Centre for Radio Astrophysics, Pune	Radio pulsar recycling: connecting the dots..	14 May 2014
Pavan Kumar Challa Kent State University, USA	Optical studies on liquid crystals made of complex shaped molecules under high magnetic fields	21 May 2014
Patrick Heyer Anton Paar Germany GmbH Germany	An enhanced rotational rheometer system with two motors for polymer rheology	26 May 2014
Les Butler Louisiana State University USA	X-ray tomography/interferometry with synchrotron and lab. sources; materials science workflows	26 May 2014
Rukmini Dey Harish-Chandra Research Institute Allahabad	Geometric quantization and coherent States	27 May 2014
Arya Dhar University of Aalto, Finland	Quasi-adiabatic dynamics in one-dimensional optical superlattices	28 May 2014
Rukmini Dey Harish-Chandra Research Institute Allahabad	Constant mean curvature surfaces	29 May 2014

Viral Parekh University of Cape Town South Africa	Morphological classification and dynamics of X-ray galaxy clusters	13 June 2014
Mohiudeen Azhar Max Planck Institute for the Science of Light, Germany	Gas filled photonic crystal fiber as a tunable "white light" source	13 June 2014
Vijay Krishnamurthy Max Planck Institute for the Physics of Complex Systems, Dresden	Mechanobiological patterns in morphogenesis	16 June 2014
Thuppil Venkatesh St. John's Medical College Bengaluru	Global and national perspectives of lead poisoning	19 June 2014
Nirmal Thyagu N Max-Planck Institute for Dynamics and Self Organization Germany	Granular slip events, electrical precursors, and the role of particle shape in jamming transition	19 June 2014
Supromany Swami South Western Railway Bengaluru	Hindi Workshop	27 June 2014
Nithyanandan T Arizona State University USA	Characterizing foreground signatures in the EoR power spectrum	1 July 2014
Mriganko Mrinmoy Roy Raman Research Institute Bengaluru	Studying the space of causal sets using Markov Chain Monte Carlo methods	10 July 2014
Dibyendu Roy Los Alamos National Laboratory USA	Strongly interacting photons in one-dimensional free space	15 July 2014
Parampreet Singh Louisiana State University USA	On some recent developments on singularity resolution in loop quantum cosmology	16 July 2014
Dominique Homberger and Ravi Rau Louisiana State University USA	A pair scientific sabbatical	16 July 2014
Rau A.R.P Louisiana State University USA	Quantum spins, real rotations, and a 1913 Ramanujan conjecture	17 July 2014
Hu Bei-Lok University of Maryland USA	Stochastic gravity theory and applications to early universe, black hole and quantum information problems	22 & 25 July 2014

Shamik Gupta Universite Paris France	Synchronization in coupled oscillator systems in presence of inertia and noise	31 July 2014
Abhiram Soori Indian Institute of Science Bengaluru	Conductance in quantum wire systems with resistances	1 August 2014
Auditya Sharma Tel Aviv University Israel	Avalanches and hysteresis in frustrated superconductors and XY spin glasses	4 August 2014
Vaibhav Wasnik Simon Fraser University Canada	Self organization in biological systems	6 August 2014
Nirupam Roy Max Planck Institute for Radio Astronomy Germany	Radio evolution of novae: results from multi-frequencing monitoring	6 August 2014
Suman Acharyya Physical Research Laboratory Ahmedabad	Master stability analysis of synchronization in coupled nearly identical oscillators	7 August 2014
Abhishek Majhi Saha Institute of Nuclear Physics Kolkata	Energy spectrum of equilibrium black holes in LQG	12 August 2014
Rakesh Joshi University of Okayama Japan	Application of nano and 2D materials	13 August 2014
Zoltan Haiman Columbia University USA	Cosmology from non-guassian weak lensing statistics	18 August 2014
Amitabha Nandi Max-Planck Institute for the Physics of Complex Systems Germany	Active mechanics and dynamics of epithelia during morphogenesis	21 August 2014
Manoj Puravankara Tata Institute of Fundamental Research Mumbai	Observing planet formation in action: Spitzer infrared spectrograph survey of protoplanetary disks in the nearby star forming regions	22 August 2014
Manpreet Singh Indian Institute of Astrophysics Bengaluru	Quantum phase transitions of bosons in two coupled 1D chains	26 August 2014
Abhijit Ghosh Weizmann Institute of Science Israel	Active dynamics of biopolymers like chromatin	1 September 2014

Shiv Visvanathan O.P Jindal Global University Sonepet	Immediate encounters: science and democracy in India	2 September 2014
Yuri Shchekinov Southern Federal University Russia	Extended OVI haloes around star-forming galaxies	3 September 2014
Anupam Kundu Universite of Paris Paris	Stochastic thermodynamics of a pair of magnetic colloids, estimation of dissipation and feedback control	9 September 2014
Smijesh N National Institute of Technology Calicut	Spectroscopy and optical time of flight studies of laser produced metal plasmas: short-pulse and ultrafast excitations	10 September 2014
Gautam Menon The Institute of Mathematical Sciences Chennai	Chromosome positioning and active matter	11 September 2014
Ujjwal Sen Harish-Chandra Research Institute Allahabad	Resonating valence bond states: A quantum information perspective	12 September 2014
Prabhu R Harish-Chandra Research Institute Allahabad	Quantum communication networks	18 September 2014
Mahadev G Savadatti	Exploring Hindi in South Indian languages	23 September 2014
Raymond Laflamme University of Waterloo Canada	Quantum information: from pure science to today's technologies	16 October 2014
Tridib Sadhu Institut de Physique Theorique France	Macroscopic fluctuation theory and its application	20 October 2014
Unnikrishnan Tata Institute of Fundamental Research Mumbai	Newton's law of motion – its origin, content and 'optics'	20 October 2014
Mallik D.C.V. Indian Institute of Astrophysics Bengaluru	K.S.Krishnan: his life and work	6 November 2014
George John University of New York USA	Functional materials – biomass as a platform for molecular design	19 November 2014

Nishant K Singh Nordic Institute for Theoretical Physics Sweden	Solar surface wave properties in the presence of hydromagnetic turbulence	21 November 2014
Aditya Chopra Australian National University Australia	The habitability of our earth and other earths	24 November 2014
Bijay Kumar Agarwalla University of California USA	Counting statistics in heat transport and fluctuation theorems	25 November 2014
Sivakumar M University of Hyderabad Hyderabad	Higher spin theories: from Dirac to Vasiliev	26 November 2014
Tomaso Belloni INAF – Osservatorio Astronomico di Brera Italy	Time variability and spectral properties of black hole binaries	1 December 2014
Aravind Natarajan University of Pittsburgh USA	The end of the dark ages	2 December 2014
Tomaso Belloni INAF-Osservatorio Astronomico di Brera Italy	Black holes and neutron stars in our galaxy as laboratories for strong gravity	3 December 2014
Anuradha Bhattacharya Saha Institute of Nuclear Physics Kolkata	AFM beyond topography and other approaches in emerging biophysics	4 December 2014
Venkataraman V Indian Institute of Science Bengaluru	Light emission from semiconductors: from infrared to blue	5 December 2014
Colin Bain Durham University United Kingdom	Drops behaving badly	12 December 2014
Ranjini Vaidyanathan Georgia Institute of Technology USA	Thermostated Kac Model	16 December 2014
Sebastian Wuester Max-Planck-Institut für Physik komplexer Systeme Germany	Towards quantum simulations of chemical and biological processes using ultra-cold Rydberg atoms	16 December 2014
Hugo Touchette Stellenbosch University South Africa	Granular Brownanian motion with solid friction	17 December 2014

Susmita Chakravorty Institut de Planétologie et d'Astrophysique de Grenoble France	Winds from the close neighbourhoods of black holes	5 January 2015
Sabitha Mohan Martin-Luther University Germany	Third-order optical nonlinearities of glass metal nanocomposites	13 January 2015
Arijit Saha University of Basel Switzerland	Transport signatures of fractional fermions in nanowires	16 January 2015
Jagdish K Vij University of Dublin Ireland	Twist bend nematic phase and its fast electroclinic effect	16 January 2015
Yashwant Gupta National Centre for Radio Astrophysics Pune	From the GMRT to Square Kilometre Array: current status and plans for the future	20 January 2015
Prerna Sharma Indian Institute of Science Bengaluru	Self assembly of colloidal rafts	23 January 2015
Guenter Werth Johannes Guthenberg University Germany	A single ion in a Penning trap: Test of QED and a new value for the electron's atomic mass	23 January 2015
Sunil Kumar Max Planck Institute for Nuclear Physics Germany	Experimental/theoretical investigations of atomic/molecular collisions with photons/charged particles	27 January 2015
Vijay Thiruvady Bangalore Environment Trust Bengaluru	Trees of Bangalore	29 January 2015
Gopalkrishna Gandhi	Gandhi's India – Gandhi Memorial lecture	30 January 2015
Gordon Love Durham University United Kingdom	A journey from astronomy to vision science	5 February 2015
Alain Omont Instut d' Astrophysique de Paris, CNRS and Universite Pierre et Marie Curie France	Millimeter/submillimeter follow-up of Herschel high-z galaxies. H_2O, a new diagnosis of their dense cores	11 February 2015
Michèle Leduc Francilien Institute for Research on Cold Atoms, France	Cold atoms for precision metrology and instruments	11 February 2015

Jeff Wagg Square Kilometre Array Organisation Jodrell Bank	On the road to Phase 1 of the Square Kilometre Array	13 February 2015
Satya Majumdar Laboratoire de Physique Théorique et Modèles Statistiques France	Diffusion with stochastic resetting	19 February 2015
Holger Schönherr University of Siegen Germany	A closer look at molecular scale processes inside polymeric vesicles by combined AFM and fluorescence lifetime imaging microscopy	24 February 2015
Vishal Gajjar Xinjiang Astronomical Observatory China	On the absence of pulses from pulsars	27 February 2015
Nayan Mani Das Indian School of Mines Dhanbad Jharkhand	Layer-by-layer investigation of nano-thin films of some amphiphilic molecules by Langmuir-Blodgett technique	6 March 2015
Sebastian Wuester Max Planck Institute for the Physics of Complex Systems Germany	Exploring links between chemical and biological processes and ultra-cold Rydberg atoms	11 March 2015
Ennio Arimondo University of Pisa Italy	Ultracold rubidium atoms excited to Rydberg levels	18 March 2015
Ennio Aromondo University of Pisa Italy	Superdiabatic quantum driving protocols for two and three level systems	19 March 2015
Ekers RD CSIRO Astronomy & Space Science Australia	Enabling technologies for modern radio astronomy: ASKAP and the phased array feeds	26 March 2015
Thomas Jennewein University of Waterloo Canada	Photonic quantum entanglement for technologies and applications; tools for the quantum internet	26 March 2015

Sl. No.	Discussed by	Paper Discussed	Date
1	Nayantara Gupta & Jagdish C. Joshi	Astrophysical Neutrinos Science **342** (2013); and Arxiv: 1405.5303	04/09/2014
2	Reji Philip & Kavya H. Rao	Pressure broadening and line narrowing in ultrafast laser produced plasmas 1. *Journal of Molecular Spectroscopy* ***122****, 16 (1987)* 2. *Principles of Plasma Spectroscopy Hans R Griem (© Cambridge University Press (1997))* 3. *Stark broadening studies on neutral and ion transitions in an ultrafast laser produced Zinc plasma* 4. *Kavya H. Rao, N. Smijesh and Reji Philip (results to be published)*	18/09/2014
3	Supurna Sinha & Kumar Shivam	Thermodynamics of Quantum Measurement Noam Erez, Phys. Scr T151 014028 (2012) iopscience.iop.org/1402-4896/2012/T151/014028	30/10/2014
4	Andal Narayanan & Nagendra G M	Quantum Memory Devices *Nature Photonics* **8**, 287 291(2014)	13/11/2014
5	Joseph Samuel & V V Prasad	Observation of self-amplifying Hawking radiation in an analogue black hole laser *Nature Physics*, 12th October, 2014, Author : Jeff Steinhauer	27/11/2014
6	Raghunathan V A & Meera Thomas	Ferromagnetism in suspensions of magnetic platelets in liquid crystal **504**, 237 (2013) Author :A. Mertelj, D. Lisjak, M. Drofenik & M. C.opic	11/12/2014
7	Vijayaraghavan D & Manjunatha M	Magnetically driven single DNA nanomotor Small, 7,601(2011) *Authors: S.Bamrungsap, J.A.Phillips, X.Xiong, Y.Kim, H.Wang, H.Liu, A.Hebard & W.Tan*	08/01/2015
8	Pramod Tadapatri	Columnar liquid crystal as a unique ferroelectric liquid crystal Fumito Araoka and Hideo Takezoe *Jpn. J. App. Phys.* **45**, 597 (2006)	12/02/2015

VISITORS

Annexure V

Name and institution	Duration of stay
Peter Heftberger University of Graz Austria	1 – 14 April 2014
Benjamin Kollmitzer University of Graz Austria	1 – 14 April 2014
Naik S Physical Research Laboratory Ahmedabad	8 – 10 April 2014
Piotr Kolenderski Copernicus University Poland	11 – 17 April 2014
Kanhaiya Lal Pandey National Centre for Radio Astrophysics Pune	14 – 20 April 2014
Sai Muthukumar V Sri Sathya Sai Institute of Higher Learning Andhra Pradesh	2 – 24 April 2014
Auditya Sharma Tel Aviv University Israel	15 April 2014 1 – 5 August 2014
Pragati Pradhan St. Joseph's College Darjeeling	20 April – 11 May 2014 20 September – 12 October 2014 18 December – 20 February 2015
Alexandre Matzki University of Cergy-Pontoise France	22 – 27 April 2014 17 – 24 August 2014
Aru Beri Indian Institute of Technology Ropar	30 April – 30 June 2014 22 November – 8 December 2014 30 January – 30 April 2015
Rahul Nigam Birla Institute of Technology & Science Hyderabad	15 – 17 May 2014
Nissim Kanekar National Centre for Radio Astrophysics Pune	15 – 18 May 2014 24 – 28 November 2014
Haripadmam PC Indian Institute of Space Science and Technology Trivandrum	20 – 22 May 2014
Kamal Sharma Bhabha Atomic Research Centre Mumbai	8 – 22 May 2014
Pritpal Kaur Sandhu Indian Institute of Technology Indore	12 May – 30 June 2014
Pavan Kumar Challa Kent State University USA	21 May 2014
Sushan Konar National Centre for Radio Astrophysics Pune	12 – 15 May 2014

Nimisha Kantharia National Centre for Radio Astrophysics Pune	19 – 26 May 2014
Rukmini Dey Harish-Chandra Research Institute Allahabad	25 May – 6 June 2014
Yogesh Maan National Centre for Radio Astrophysics Pune	25 May – 10 June 2014 2 – 9 December 2014
Les Butler Louisiana State University USA	26 May 2014
Patrick Hayer Anton Paar Germany GmbH Germany	26 May 2014
Arya Dhar Aalto University Finland	28 May 2014
Jinto Thomas Institute of Plasma Research Ahmedabad	28 – 30 May 2014
Seshadri T.R. Delhi University New Delhi	14 – 16 April 2014 30 May 2014
Viral Parekh University of Capetown South Africa	1 – 30 June 2014
Chirag Kalelkar Indian Institute of Technology Kharagpur	2 – 22 June 2014
Nirmal Thyagu Max-Planck Institute for Dynamics & Self-Organization Germany	19 June 2014
Ruta Kale INAF-Instituti di Radioastronomia Italy	22 – 30 June 2014
Siddharth Malu Indian Institute of Technology Indore	22 June – 10 July 2014
Nithyanandan T Arizona State University USA	22 June – 7 August 2014
Nidya Rajesh and Rita Doc College Madurai	24 – 25 June 2014
Swapnesh Panigrahi Institute of Physics France	6 – 27 July 2014
Rau ARP Louisiana State University USA	11 – 18 July 2014
Dibyendu Roy Center for Non-linear Studies USA	14 – 19 July 2014

Julien Fade Institute of Physics France	14 July – 1 August 2014
Parampreet Singh Louisiana State University USA	16 – 17 July 2014
Bei-Lok Hu University of Maryland USA	19 – 26 July 2014
Govind Swarup National Centre for Radio Astrophysics Pune	31 July – 1 August 2014
Shamik Gupta Universite Paris France	31 July 2014
Uttam Singh Chandra Research Institute Allahabad	31 July – 15 August 2014
Abhiram Soori Indian Institute of Science Bengaluru	1 August 2014
Nirupam Roy Max Planck Institute for Radio Astronomy Germany	6 August 2014
Vaibhav Wasnik Simon Fraser University Canada	5 – 8 August 2014
Suman Acharya Physical Research Laboratory Ahmedabad	6 – 9 August 2014
Abhishek Majhi Saha Institute of Nuclear Physics Kolkata	11 – 14 August 2014
Rakesh Joshi University of Okayama Japan	13 August 2014
Arun K Pati Harish-Chandra Research Institute Allahabad	12 – 15 August 2014
Yuri Shchekinov Southern Federal University Russia	13 August – 9 September 2014
Dipankar Home Bose Institute Kolkata	17 – 26 August 2014
Zoltman Haiman Columbia University USA	18 August 2014
Amitabha Nandi Max-Planck Institute for the Physics of Complex Systems Germany	20 – 22 August 2014
Manoj Puravankara Tata Institute of Fundamental Research Mumbai	22 August 2014

Eugene Vasiliev Southern Federal University Russia	25 August – 25 September 2014
Abhijit Ghosh Weizmann Institute of Science Israel	31 August – 3 September 2014
Sanjay Puri Jawaharlal Nehru University New Delhi	1 – 2 September 2014
Utkarsh Mishra Harish-Chandra Research Institute Allahabad	7 – 16 September 2014
Shevgaonkar R.K. Indian Institute of Technology Delhi	11 September 2014
Anupam Kundu Universite Paris France	9 September 2014
Ujjwal Sen Harish-Chandra Research Institute Allahabad	11 – 14 September 2014
Surajit Dhare University of Hyderabad Hyderabad	16 – 18 September 2014
Prabhu R Harish-Chandra Research Institute Allahabad	16 – 19 September 2014
Aditi Sen De Harish-Chandra Research Institute Allahabad	16 – 19 September 2014
Asha K Kuvempu University Shimoga	22 – 24 September 2014
Mamta Gulati Indian Institute of Science Education and Research Mohali	25 September – 3 October 2014 20 – 28 February 2015
Analabha Roy Institute of Nuclear Physics Kolkata	28 September – 1 October 2014
Raymond Laflamme University of Waterloo Canada	14 – 18 October 2014
Tridib Sadhu Institute de Physique Theorique CEA/Saclay France	18 – 22 October 2014
Sushil Mujumdar Tata Institute of Fundamental Research Mumbai	19 – 20 October 2014
Unnikrishnan C.S. Tata Institute of Fundamental Research Mumbai	20 – 24 October 2014
Tirthankar Roychowdhury National Centre for Radio Astrophysics Pune	19 – 22 October 2014

Anusha Thilakan University of Hyderabad Hyderabad	12 – 14 November 2014
George John University of New York USA	19 November 2014
Nishant K Singh NORDITA Sweden	20 – 27 November 2014
Aditya Chopra Australian National University Australia	23 – 24 November 2014
Raghwinder Singh Indian Institute of Physics Madras	24 – 30 November 2014
Bijay Kumar Agarwalla University of California USA	25 November 2014
Sivakumar M University of Hyderabad Hyderabad	26 November 2014
Siji Narendran National Institute of Technology Calicut	27 – 28 November 2014
Tomoso Belloni Obserraterio Astronomico di Brera Italy	28 November – 5 December 2014
Aravind Natarajan University of Pittsburg USA	2 December 2014
Anuradha Bhattacharya Saha Institute of Nuclear Physics Kolkata	4 December 2014
Rafael Sorkin Perimeter Institute for Theoretical Physics Canada	10 December 2014 – 13 January 2015
Colin Bain Durham University United Kingdom	12 December 2014
Jinto Thomas Institute of Plasma Research Ahmedabad	15 – 16 December 2014
Ranjini Vaidyanathan Georgia Institute of Technology USA	16 December 2014
Hugo Touchette Stellanbosch University South Africa	16 – 19 December 2014
Susmita Chakravorty Joseph Fourier University France	4 – 8 January 2015
Sabitha Mohan Martin-Luther University Germany	11 – 14 January 2015

Petros Wallden University of Edinburgh United Kingdom	11 – 17 January 2015
David Rideout University of California USA	11 – 18 January 2015
Ian Jubb Imperial College London	11 – 24 January 2015
Jagdish K Vij University of Dublin Ireland	14 – 16 January 2015
Arijit Saha University of Basel Switzerland	13 – 17 January 2015
Yashwant Gupta National Centre for Radio Astrophysics Pune	18 – 20 January 2015
Guenter Werth Johannes Guthenberg University Germany	21 – 25 January 2015
Leela and Rakesh Kumar University of Hyderabad Andhra Pradesh	28 – 30 January 2015
Gordan Love Durham University United Kingdom	5 – 12 February 2015
Michele Leduc Francilien Institute for Research on Cold Atom France	10 – 11 February 2015
Alain Omont CNRS and Universite Pierre et Marie Curie France	10 – 12 February 2015
Jean Michel Chasseriaux Lysios Public Affairs Paris	10 – 11 February 2015
Satya Majumdar LPTMS France	11 – 20 February 2015
Jef Wagg Square Kilometre Array Organisation United Kingdom	13 February 2015
Muthukumar M University of Massachusetts USA	15 – 20 February 2015
Saptarishi Chaudhuri National University of Singapore Singapore	18 – 20 February 2015
Nipanjana Patra University of California USA	21 – 26 February 2015
Holger Schonner University of Siegen Germany	24 February 2015

Divya Philips National Institute for Interdisciplinary Science and Technology Trivandrum	25 – 26 February 2015
Vishal Gajjar Xinjiang Astronomical Observatory China	27 February 2015
Anirban Sain Indian Institute of Technology Mumbai	4 – 5 March 2015
Nayan Mani Das Indian School of Mines Dhanbad	4 – 6 March 2015
Dipankar Home Bose Institute Kolkata	17 – 24 August 2014 6 – 13 March 2015
Sebastian Wuester Max-Planck-Institut für Physik Komplexer Systeme Germany	11 – 14 March 2015
Ron Ekers Australia Telescope National Facility Australia	11 – 27 March 2015
Ennio Aromondo University of Pisa Italy	15 – 20 March 2015
Maria Allegrini University of Pisa Italy	15 – 20 March 2015
Vikram Vyas Delhi University Delhi	15 – 21 March 2015
Arun K Singh PEC University of Technology Chandigarh	17 – 20 March 2015
Kishore Sridharan Hangyang University South Korea	19 – 20 March 2015
Thomas Jennewein University of Waterloo Canada	25 – 29 March 2015

VISITING STUDENTS' PROGRAMME

Annexure VI

Sl.	Student	Mentor
1	Guruprasad A.R.	Prabu T
2	Krishna Priya S R	Andal Narayanan
3	Swapna T.	Pratibha R
4	Dharmendra Prasad Shukla	Ranjini Bandyopadhyay
5	Shreya Ray	Urbasi Sinha
6	Chaitra G V	Srivani K S
7	Bhargavi M	Srivani K S
8	Jake Cohen	Lakshmi Saripalli
9	Ashwini G	Ravi Subrahmanyan
10	Rashmi M.R.	Hema Ramachandran
11	Chandan K J	Somashekar R
12	Nikhil B V	Somashekar R
13	Madhu K	Ramesh B
14	Satish K.T.	Prabu T
15	Sandeep P	Prabu T
16	Supravika Hegde M.R.	Raghunathan A
17	Rashi Shroff	Deshpande A A
18	Pranitha Sankar	Reji Philip
19	Soumya Hegde	Deshpande A A
20	Kashyap N	Udaya Shankar N
21	Akshay G H	Udaya Shankar N
22	Kiran Kumar B.M.	Ramesh B
23	Jayasheel R	Udaya Shankar N
24	Karishma Bansal	Deshpande A A
25	Shyam Narayan S.	Prabu T
26	Ashwini R	Prabu T
27	Ashwini S	Prabu T
28	Sachin B S	Udaya Shankar N
29	Ishani Salaria	Deshpande A A
30	Rishyashringa J.S.	Vijayaraghavan D
31	Chittaspandini Kulkarni	Raghunathan V A
32	Sebanti Chattopadhyay	Supurna Sinha

33	Hafsa Syed	Ranjini Bandyopadhyay
34	Sonakshi Sachdev	Joseph Samuel
35	Sumit Haldar	Arun Roy
36	Elizabeth Noble	Reji Philip
37	Supriya D M	Pratibha R
38	Neha Mahendarkar V	Ruckmongathan T N
39	Sreekanth P	Reji Philip
40	Boina Shrilakshmi	Gautam Soni
41	Dinesh Raut	Shiv K Sethi
42	Nagendra G M	Andal Narayanan
43	Anjali P.S.	Urbasi Sinha
44	Rajsekhar Das	Ranjini Bandyopadhyay
45	Souvik Biswas	Ravi Subrahmanyan
46	Pavan C M	Ruckmongathan T N
47	Apoorva Joshi	Ravi Subrahmanyan
48	Maria Kuruvilla	Deshpande A A
49	Simin Meshk	Arun Roy
50	Sunny Sourabh	Hema Ramachandran
51	Nidhin P	Srikant R
52	Praveen Kumar M	Hema Ramachandran
53	Neethu Varghese	Gautam Soni
54	Bala Vignesh	Udaya Shankar N
55	Prathwiraj U	Udaya Shankar N
56	Himanshu Badhani	Joseph Samuel
57	Shashank Gupta	Pratibha R
58	Anand Sahay	Lakshmi Saripalli
59	Bhushan S. Shenvi	Shiv K Sethi
60	Snehalatha TKAC	Ramesh B
61	Niranjan V K	Ramesh B
62	Durvasa Gupta Y	Gautam Soni
63	Karthigeyan R	Ramesh B
64	Kulkarni Abhay Prakash	Ramesh B
65	Ganesh B G	Jacob Rajan
66	Pratik Solanki	Sandeep Kumar

67	Jelina Dsouza	Supurna Sinha
68	Sarayoo Sasidharan K	Reji Philip
69	Ashvini Purohit	Hema Ramachandran
70	Arun M	Shiv K Sethi
71	Jayesh A. Bafna	Gautam Soni
72	Vinaya Kumara D.R.	Sandeep Kumar
73	Amit Kumar	Pramod Pullarkat
74	Praveen M N	Somshekar R
75	Isha Kotecha	Sumati Surya
76	Ashwini G	Dwarakanath K S
77	Rengaraj G	Urbasi Sinha
78	Aditya P.M.	Ramesh B
79	Lakshmi Sindhu	Hema Ramachandran
80	Yuvraj Joshi	Gautam Soni
81	Ranjana Doddamani P	Pratibha R
82	Vishnu M	Hema Ramachandran
83	Dibyashree Koushik	Reji Philip
84	Pradeep Kumar N	Urbasi Sinha
85	Animesh Aaryan	Urbasi Sinha
86	Sourabha T T	Gautam Soni
87	Divya A P	Hema Ramachandran
88	Kavya H Rao	Reji Philip
89	Anil Kumar Tolamatti	Bala R Iyer
90	Shruthi Sudhakar	Deshpande A A
91	Deepa A	Gautam Soni
92	Rajaram K	Bala R. Iyer
93	Raj Biswas	Deshpande A A
94	Sai Krishna	Deshpande A A
95	Piyush Kumar Sinha	Hema Ramachandran
96	Radhika Joshi	Deshpande A A
97	Juhi Tiwari	Deshpande A A
98	Aman Choksi	Ravi Subrahmanyan
99	Avinash	Shiv K Sethi
100	Supreet Kulkarni	Gautam Soni

101	Swapnil Narke	Deshpande A A
102	Manjunatha M	Vijayaraghavan D
103	Akshit Kumar	Hema Ramachandran
104	Susav Pradhan	Pramod Pullarkat
105	Sriram Sudarshanam	Hema Ramachandran
106	Pradeep Singh	Srivani K S
107	Deepak Kumar Deo	Lakshmi Saripalli
108	Anita Rose Thomas	Reji Philip
109	Pranav R. Saghvi	Deshpande A A
110	Neha Tanushree	Gautam Soni
111	Manish Kumar	Sandeep Kumar
112	Sindhana Selvi P S	Supurna Sinha
113	Sree Vani J	Dwarakanath K S
114	Sudhi Oberoi	Urbasi Sinha
115	Shivi Shetty	Sadiq Rangwala
116	Alka Bhat	Pramod Pullarkat
117	Swati Kaushik	Gautam Soni
118	Manasa Manjunath	Sumati Surya
119	Santosh Harish	Udaya Shankar N
120	Harikrishnan A	Andal N
121	Rahul S. Kingar	Deshpande A A
122	Sanal V	Hema Ramachandran
123	Moumita Adhikari	Gautam Soni
124	Siva Pradyumna	Urbasi Sinha
125	Soham Kumar Dutta	Arun Roy
126	Adwait P. Suratkar	Gautam Soni
127	Bharath Krishnan	Ramesh B
128	Madhurima Choudhury	Deshpande A A
129	Manikandan K	Gautam Soni
130	Prem J	Ramesh B
131	Anjali Sharma	Pratibha R
132	Gayatri Patel	Deshpande A A
133	Manjunath A S	Vijayaraghavan D
134	Ashwini Mohan	Reji Philip

135	Lakshay Khurana	Hema Ramachandran
136	Rose Martina P A	Hema Ramachandran
137	Swetha G S M	Hema Ramachandran
138	Aswani I C	Hema Ramachandran
139	Krishnaprasad C	Lakshmi Saripalli
140	Shankar M J	Hema Ramachandran
141	Seraj Uddin Ansari	Hema Ramachandran
142	Sharanya A	Gautam Soni
143	Priyanka Bhatt	Sadiq Rangwala
144	Bhagyashri Devaru Bhat	Arun Roy
145	Phalguni Mathur	Ramesh B
146	Arvind Kumar	Gautam Soni
147	Kiran Narayana Hegde	Somashekar R
148	Meenu	Pratibha R
149	Poojitha C G	Vijayaraghavan D
150	Juhi Tiwari	Shiv K Sethi

RAMAN RESEARCH INSTITUTE
BANGALORE



STATEMENT OF ACCOUNTS
2014 - 2015

RAMAN RESEARCH INSTITUTE

Bangalore

Audited Statements of Account

2014-2015

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
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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 2015, 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 subject to the following observation:

.....2

G.R. VENKATANARAYANA Chartered Accountant BANGALORE

(i) The amount spent on acquisition of fixed assets has been deducted from the total grants/ subsidies received in the Income & Expenditure account. This is not in conformity with the Accounting Standard- 5 issued by the Institute of Chartered Accountants of India. It has been explained that this format has been consistently used to present the accounts before the authority who grant the funds.

5. In our opinion and to the best of our information and according to the explanations given to us and subject to notes on accounts and our qualifications in para 4 above, 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, 2015; 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

Place: Bangalore
Date: 18.08.2015

M/s. G.R. VENKATANARAYANA
Chartered Accountants
618, 75th Cross, 6th Block
Rajajinagar, BANGALORE-560 010

RAMAN RESEARCH INSTITUE

Bangalore

Balance Sheet as at 31st March 2015

I SOURCES OF FUNDS	SCH.	As at 31.3.2015 Rs.	As at 31.3.2014 Rs.
CAPITAL FUND	1	103,40,70,278	106,27,08,808
GENERAL FUND	2	63,12,823	89,87,976
RETIREMENT FUNDS	3	31,59,54,939	33,05,55,749
UNUTILISED GRANTS	4	3,59,142	95,53,864
SUNDRY CREDITORS	5	4,48,43,702	1,34,33,220
PROVIDENT FUND (contra)	6	10,90,33,055	10,72,09,969
PENSION FUND (contra)	7	9,33,72,561	8,42,43,409
TOTAL		160,39,46,500	161,66,92,995

II APPLICATION OF FUNDS			
FIXED ASSETS	8	89,40,25,934	91,35,58,453
INVESTMENTS - RETIRMENT FUND	9	31,59,54,939	33,05,55,749
CURRENT ASSETS, ADVANCES AND DEPOSITS	10	16,83,83,229	14,34,51,298
CASH AND BANK BALANCES	11	2,31,76,782	3,76,63,117
PROVIDENT FUND (contra)	12	10,90,33,055	10,72,09,969
PENSION FUND (contra)	13	9,33,72,561	8,42,43,409
TOTAL		160,39,46,500	161,66,81,995

Notes on accounts. 17

Schedules 1 to 17 form an integral part of the accounts

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

Place : Bangalore
Date : August 18, 2015

RAMAN RESEARCH INSTITUTE

Bangalore

Income and Expenditure Account for the year ended 31.03.2015

A INCOME	SCH.	2014-2015 Rs.	2013-2014 Rs.
GRANT-IN-AID:			
Non-Plan-Recurring		81,98,903	84,75,000
Plan-Recurring		28,94,44,510	27,48,84,330
Transfer from Commutation Fund		92,75,440	
Interest & Miscellaneous Income	14	14,17,500	1,32,83,023
TOTAL (A)		30,83,36,353	29,66,42,353
B EXPENDITURE			
Salaries & Allowances	15	20,57,82,960	19,31,59,355
Working Expenses	16	10,52,17,546	10,22,99,692
TOTAL(B)		31,10,00,506	29,54,59,047
C SURPLUS/(DEFICIT)FOR THE YEAR (A-B)		-26,64,153	11,83,306

Notes on accounts. 17
Schedules 1 to 17 form an integral part of the accounts

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

Place : Bangalore
Date : August 18, 2015

RAMAN RESEARCH INSTITUTE
Bangalore

Receipts and Payments account for the year ended 31.03.2015

RECEIPTS	SCH.	2014-2015 Rs.	2013-2014 Rs.
Opening Balance	A	41,14,568	11,61,696
Grant-in-aid	B	35,30,45,828	33,44,30,040
Miscellaneous Receipts	C	21,79,120	1,41,06,229
Deposits and other Items	D	4,34,28,125	4,16,58,740
Short term Bank Deposits & Investments		61,37,49,413	78,90,32,482
TOTAL		101,65,17,054	118,03,89,187

PAYMENTS			
Recurring Expenditure (Plan and Non-Plan)	E	30,90,97,792	29,74,66,347
Plan - Non-Recurring(Capital) Expenditure	F	5,76,70,963	7,63,44,329
Expenditure out of Grants/ Assistance from Government Agencies	G	47,37,235	94,17,048
Advance to Suppliers	H	8,93,989	1,52,24,672
Deposits and other items	I	4,07,39,429	4,38,22,223
Short term Bank Deposits & Investments		59,57,09,914	73,40,00,000
Closing Balance	J	76,67,732	41,14,568
TOTAL		101,65,17,054	118,03,89,187

Notes on accounts. 17
Schedules 1 to 17 form an integral part of the accounts

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 0

Place : Bangalore
Date : August 18, 2015

RAMAN RESEARCH INSTITUTE

Bangalore

Schedules forming part of the Audited Statements of Account for the year ended 31st March 2015

PARTICULARS		As on 31.03.2015 Rs.	As on 31.03.2014 Rs.
SCHEDULE - 1			
Capital Fund			
Balance as on 1.4.2014		106,27,08,808	103,69,32,812
Add: Assets acquired/transferred during the year			
1) Plan - Non - Recurring (Capital)		5,76,70,963	7,63,44,329
2) Scientific Publications acquired during the year			1,05,14,977
3) Advance to Suppliers (net)		8,93,989	1,52,24,672
		112,12,73,760	113,90,16,790
Less: Assets deleted during the year	1,25,27,729		
Less : Accu.depn.(Vide Sch.8 col. 9)	53,55,604	71,72,125	53,54,179
Less: Amount transferred to Capital Expn.		1,00,00,000	
		110,41,01,635	113,36,62,611
Less: Depreciation		7,00,31,357	7,09,53,803
TOTAL		103,40,70,278	106,27,08,808
SCHEDULE - 2			
General Fund			
Balance as on 1.4.2014		89,76,976	77,93,670
Add/((Less) : Surplus/ (Deficit) for the year		-26,64,153	11,83,306
TOTAL		63,12,823	89,76,976

PARTICULARS		As on 31.03.2015 Rs.	As on 31.03.2014 Rs.
SCHEDULE - 3			
Retirement Funds - vested with SBI Life Insurance			
1. Gratuity Fund			
Opening Balance	7,60,03,347		
Add : Interest earned	58,88,342		
Less: Claims paid	89,75,026		
		7,29,16,663	7,60,03,347
2. Leave Salary			
Opening Balance	6,32,42,513		
Add : Interest earned	49,18,502		
Less: Claims paid	72,41,114		
		6,09,19,901	6,32,42,513
3. Commutation of Pension Fund			
Opening Balance	19,13,09,889		
Add : Interest earned	1,57,52,543		
Less: Claims paid	2,49,44,057	18,21,18,375	19,13,09,889
TOTAL		31,59,54,939	33,05,55,749
SCHEDULE - 4			
Unutilized Grants			
Plan Non- Recurring(Capital)		1,21,736	95,53,864
Plan - Salaries		55,118	
Plan - General		1,82,288	
TOTAL		3,59,142	95,53,864

PARTICULARS		As on 31.03.2015 Rs.	As on 31.03.2014 Rs.
SCHEDULE - 5			
Sundry Creditors			
a. Un-Utilised Grants - Projects/Meetings etc.,			
1. Enabling New Sciences- MWA		36,269	36,269
2. DBT - Ramalingaswami Re-entry Fellowship		72,801	
3. DBT - Biomechanics of synaptogensis		7,321	7,321
4. Ramanujan Fellowship		2,06,447	
5. INSA Fellowship			33,418
6. Theiss Research Programme		34,951	
7. IFCPAR Research Project		1,37,525	1,37,525
8. Indo-Australian(BMWF) Joint Research		70,579	1,55,000
9. Implementation of India & Russia basic Science		4,73,600	4,73,600
b. Others			
1. Earnest Money Deposits		6,07,000	6,70,794
2. Contractors' Security Deposits		10,74,703	10,95,967
3. Group Insurance Scheme		691	1,641
4. Indian Academy of Sciences (for Land)		1,00,00,000	1,00,00,000
5. Service benefits and other liabilities		1,35,922	6,09,985
6. Caution Deposits (Hostel)		1,72,500	1,71,000
7. Profession Tax		39,000	40,700
8. SBI - Life - Commutation of Fund Payable		1,84,85,525	
9. RRI Trust		25,788	
10.RRI Pension Fund A/c		30,51,377	
11.Sundry Creditor		2,11,703	
12.Earmarked for Registration of Land		1,00,00,000	
		4,48,43,702	1,34,33,220
SCHEDULE - 6			
Provident Fund			
FUND BALANCES:			
A. Employees Subscription			
a) Contributory Provident Fund		4,00,91,760	3,96,78,747
b) General Provident Fund		2,36,94,605	2,20,45,037
B. Institute Contribution to Contributory Provident Fund		3,30,70,140	3,36,94,545
C. New Pension Scheme		12,51,894	8,26,817
GENERAL FUND -	1,09,64,824		
Less: Excess of expenditure over income for 2014-15	-13,27,205		
		96,37,619	1,09,64,823
RRI Pension Fund		12,87,037	
TOTAL		10,90,33,055	10,72,09,969
SCHEDULE - 7			
Pension Fund			
Capital Fund-Opening Balance	8,19,82,300		8,19,82,300
Add: Institute's Contribution for the year (Corpus Fund)	36,18,336		
Add : G P F Contribution for the year	29,22,666		
Add: Transferred from CPF	48,49,259		
		9,33,72,561	
Raman Research Institute - P F Account			22,61,109
TOTAL		9,33,72,561	8,42,43,409

SCHEDULE - 8
Fixed Assets

Sl.No	DESCRIPTION	GROSS BLOCK					DEPRECIATION BLOCK				NET BLOCK	
		Original Cost as on 01.04.2014	Addition during the year	Deletion during the year	Original cost as on 31.03.2015	Rate	Total up to 01.04.2014	Less Accu.Depn.on Deletion (on col. No.5)	For the year 2014-2015 (on Col.No.6)	Total up to the end of 31.03.2015 (8-9+10)	As on 31.03.2015 (6-11)	As on 1.04.2014
1	2	3	4	5	6	7	8	9	10	11	12	13
		Rs.	Rs.	Rs.	Rs.	%	Rs.	Rs.	Rs.	Rs.	Rs.	Rs.
1	Land											
	(a) R M V II Stage	3,78,735			3,78,735						3,78,735	3,78,735
	(b) Malleswaram	31,19,436			31,19,436						31,19,436	31,19,436
	(c) H M T, Jalahalli	8,00,63,261			8,00,63,261						8,00,63,261	8,00,63,261
2	Building	17,03,04,661	31,58,863		17,34,63,524	1.63	2,43,18,797		28,27,455	2,71,46,252	14,63,17,272	14,59,85,864
3	Capital Equipment	79,23,34,914	4,72,15,668	1,25,27,729	82,70,22,853	4.75	26,41,45,209	53,55,604	3,92,83,586	29,80,73,190	52,89,49,663	52,81,89,705
4	Canteen Infrastructure	42,76,021			42,76,021	4.75	8,12,444		2,03,111	10,15,555	32,60,466	34,63,577
5	Computers	14,81,47,392	50,72,537		15,32,19,929	16.21	14,05,58,298		1,55,46,038	15,61,04,336	-28,84,407	75,89,094
6	Furniture & Fixture	1,30,41,056	6,59,164		1,37,00,220	6.33	64,14,998		8,67,224	72,82,222	64,17,998	66,26,058
7	Vehicles	50,09,321			50,09,321	9.50	38,08,427		4,75,885	42,84,313	7,25,008	12,00,894
8	Books and Journals	22,63,94,385	15,64,731		22,79,59,116	4.75	8,94,52,556		1,08,28,058	10,02,80,614	12,76,78,502	13,69,41,829
	TOTAL	144,30,69,182	5,76,70,963	1,25,27,729	148,82,12,416		52,95,10,729	53,55,604	7,00,31,357	59,41,86,482	89,40,25,934	91,35,58,453

PARTICULARS	As on 31.03.2015 Rs.	As on 31.03.2014 Rs.
SCHEDULE - 9		
Investments - Retirement Funds - vested with SBI Life Insurance		
Gratuity Fund	7,29,16,663	7,60,03,347
Leave Salary	6,09,19,901	6,32,42,513
Commutation of Pension Fund	18,21,18,375	19,13,09,889
TOTAL	31,59,54,939	33,05,55,749
SCHEDULE - 10		
Current Assets, Advances and Deposits		
a) Stock on Hand	10,06,416	14,01,170
b) Advances and Deposits:		
1. Advance to Suppliers	3,98,56,433	3,89,62,445
2. Advance for purchase of Land	8,89,61,800	8,89,61,800
3. Advances to Staff	29,89,067	54,81,111
4. Other Advances/Deposits	23,69,479	21,59,548
5. Tax Deducted at Source	53,721	17,856
6. Indian Academy of Sciences	6,271	6,271
7. Ramanujan Fellowship		15,47,951
8. Customs Duty Receivable		27,91,120
9. TIFR		77,810
10. CSIR - Extra Murual Research project	5,40,000	3,60,000
11. ISRO - for SSO Project	1,09,961	1,09,961
12. CSIR - Jr. Research Fellowship	38,524	2,22,391
13. Australia-India Strategic Research Fund	4,820	4,820
14. SBI LIFE	44,68,658	11,53,522
15. DBT - Ramalingaswami Re-entry Fellowship		1,93,522
16. Grants Receivable	2,79,78,079	
TOTAL (a+b)	16,83,83,229	14,34,51,298
SCHEDULE - 11		
Cash and Bank Balances		
Cash at Banks - In Savings Bank Accounts/MODs :		
State Bank of India	1,03,24,833	32,49,860
State Bank of Mysore	66,35,761	28,57,819
Canara Bank	2,16,177	5,15,923
Union Bank of India	59,62,141	3,10,21,535
Central Bank of India	18,777	17,695
Stamps on hand (Franking Machine)	19,093	285
TOTAL	2,31,76,782	3,76,63,117

PARTICULARS	As on 31.03.2015 Rs.	As on 31.03.2014 Rs.
SCHEDULE - 12		
Provident Fund		
Investments (At Cost)	9,45,30,517	9,11,13,889
Refundable Advances	2,22,380	5,01,800
Interest earned on Investments	3,94,295	16,94,495
Income-tax Deducted at Source Receivable	5,39,000	4,67,349
Raman Research Institute Pension Fund A/c		22,61,109
Cash at Banks:		
State Bank of India	1,15,38,690	50,92,697
HDFC Bank	18,08,173	60,78,630
TOTAL	*10,90,33,055*	10,72,09,969
SCHEDULE - 13		
Pension Fund		
Investments (At Cost)	5,66,18,214	5,68,06,484
Interest earned on investments	7,25,038	12,90,178
Income-tax deducted at source	3,40,103	3,92,654
Raman Research Institute	2,81,70,243	1,78,51,270
Raman Research Institute (PF A/c)	12,87,037	
Cash at Banks:		
Central Bank of India	6,07,738	3,29,238
State Bank of India (S B A/c)	24,82,455	12,95,899
State Bank of India (MOD A/c)	26,14,256	20,98,187
HDFC Bank	5,27,477	41,79,499
TOTAL	9,33,72,561	8,42,43,409
SCHEDULE - 14		
Interest & Miscellaneous Income		
Interest on :		
Letters of Credit Margins		5,07,188
Short Term Deposits & Savings Bank A/cs		80,72,461
Miscellaneous Income		
Grant-in-aid from -		
Raman Research Institute Trust	1,00,000	1,00,000
License fee from quarters	4,50,487	4,26,356
Other Receipts	5,91,209	10,03,667
Sale of unserviceable items	2,75,804	31,73,351
TOTAL	14,17,500	1,32,83,023
SCHEDULE - 15		
Salaries & Allowances		
Pay	6,93,19,771	6,34,62,422
Allowances	9,44,65,513	8,55,30,407
Medical Reimbursement	63,05,920	62,79,867
Leave/Home Travel Concession	20,58,717	14,84,929
Leave Salary Encashment - LTC	9,41,538	6,58,304
Contributions towards :		
Retirement Funds	28,48,827	86,97,080
Provident Fund	17,86,002	19,87,540
Pension Fund	28,76,885	46,91,409
N P S Contribution	16,53,501	14,13,801
SBI Life Insurance - Annual premia	91,800	
Shortfall in Pension	1,78,51,270	1,50,25,628
Travelling Expenses	55,83,216	39,27,968
TOTAL	20,57,82,960	19,31,59,355

PARTICULARS	As on 31.03.2015 Rs.	As on 31.03.2014 Rs.
SCHEDULE - 16 **Working Expenses**		
Wages	5,66,225	3,38,500
Honoraria and Professional Fees	18,70,472	16,07,635
Printing, Stationery (Schedule - 16 A)	12,89,339	13,48,235
Telephone and Communication Charges	25,31,681	30,84,252
Electricity Charges (including maintenance of generators)	1,04,59,176	1,01,69,414
Water Charges	6,57,534	4,56,324
Advertisement	1,98,795	69,813
Vehicle Maintenance/Transport	22,55,080	19,77,469
Liveries and Uniforms	2,28,993	2,34,883
Postage and Courier Services	1,36,294	1,86,908
Seminars/Conferences/Colloquia, Summer School Programme etc.,	12,57,955	29,62,723
Bank Charges	8,470	6,840
Amenities	14,59,922	12,23,620
Crèche	2,40,000	2,40,000
Entertainment and Hospitality	3,39,354	2,85,178
Audit fee	47,191	47,191
Repairs and Maintenance	92,70,442	85,89,790
Campus Maintenance	77,53,650	74,17,815
Payroll processing charges	3,21,631	3,67,639
Security	72,89,793	69,79,615
Stores and Consumables (Schedule - 16 A)	2,57,58,099	2,06,09,986
Project Working Expenses	66,36,437	41,53,035
Subscriptions to Journals & Publications	75,79,826	1,09,70,469
Ph.D. Programme	41,91,188	42,83,058
Pancharatnam Fellowship		96,592
Lease Rent of Land	4,39,172	2,71,092
Corporation Taxes	3,04,018	3,04,018
Freight, etc.	3,93,200	2,36,596
Conveyance	4,05,707	3,96,698
Visiting Students Programme	79,87,341	82,31,549
Inter Institutional Collaboration & Visiting Scientists' expenses	21,70,795	26,23,157
Outreach	1,59,399	6,49,356
Patent Fees	2,32,995	9,65,459
Miscellaneous Expenses	4,77,372	6,14,783
Affiliation Fee for Universities	3,00,000	3,00,000
TOTAL	10,52,17,546	10,22,99,692

SCHEDULE - 16 - A

Stores / Consumables & Stationery items

SL. NO.	DESCRIPTION	OPENING STOCK AS ON 1.4.2014	PURCHASE DURING THE YEAR	LESS:CLOSING STOCK AS ON 31.3.2015	CONSUMPTION DURING THE YEAR
		Rs.	Rs.	Rs.	Rs.
1	Stores and Consumables	10,47,347	2,53,97,612	6,86,860	2,57,58,099
2	Printing & Stationery	3,53,823	12,55,072	3,19,556	12,89,339
	TOTAL	14,01,170	2,66,52,684	10,06,416	2,70,47,438

PARTICULARS			2014-2015 Rs.	2013-2014 Rs.
SCHEDULE - A				
Opening Balance				
Cash at Banks -				
State Bank of India			3,08,397	71,886
State Bank of Mysore			28,57,819	3,51,859
Canara Bank			5,15,923	1,65,348
Union Bank of India			4,14,449	5,52,031
Central Bank of India			17,695	17,008
Stamps on hand			285	3,564
TOTAL			41,14,568	11,61,696
SCHEDULE - B				
Grants-in-aid				
a) Ministry of Science & Technology (Department of Science & Technology)				
1. Non-Plan Recurring		76,28,000		84,75,000
Add : Interest earned on HBA etc.,advances		4,44,654		
Add : Interest earned		1,26,249	81,98,903	
2. Plan Recurring :				
i) Salaries & Allowances		17,54,07,000		
Add : Interest earned		29,03,106	17,83,10,106	
ii) S C & S T Expenses		1,10,25,000		
Add : Interest earned		1,82,472	1,12,07,472	
iii) General		9,83,00,000		27,48,84,330
Add : Interest earned		16,26,932	9,99,26,932	
3. Plan Non-Recurring		2,93,33,000		4,66,15,670
Add : Interest earned LC margins		8,49,110		
Add : Interest earned		4,85,481	3,06,67,591	
4. Swarna Jayanthi Fellowship				15,00,000
5. Implementation of India & Russia Basic Science				4,73,600
6. Indo-Austrian (BMWF) Joint Research				1,55,000
7. Ramanujam Fellowship			30,00,000	3,12,120
8. DBT - Ramalingaswami Re-entry Fellowship			20,81,000	
b) INSA - Fellowship				2,30,000
c) CSIR - Extra Murual Research project				3,60,000
d) CSIR - Jr. Research Fellowship			2,82,667	
e) IFCPAR Research Project				14,24,320
f) Theiss Research Programme			13,15,268	
g) TIFR			77,810	
Transfer from Commutation Fund Receipt (SBI Life Fund)				
i) Plan General			50,78,148	
ii) Plan Salaries			44,34,698	
iii) Plan Capital			84,65,233	
TOTAL			35,30,45,828	33,44,30,040

PARTICULARS	2014-2015 Rs.	2013-2014 Rs.
SCHEDULE - C **Miscellaneous Receipts**		
Grant-in-aid from Raman Research Institute Trust	1,00,000	1,00,000
License fee from staff quarters	4,50,487	4,26,356
Interest on Letters of Credit Margins		5,07,188
Interest on Short term Deposits & SB Accounts		80,72,461
Other Receipts	5,91,209	10,03,267
Sale of unserviceable items	2,75,804	31,73,751
Recoveries/Adjustments of Advance		
Conveyance Advance	1,62,540	1,94,150
House Building Advance	3,12,917	3,09,418
Festival Advance	1,84,275	1,92,450
Computer Advance	1,01,888	1,27,188
TOTAL	21,79,120	1,41,06,229
SCHEDULE - D **Deposits and other items**		
Recoveries from Staff towards:		
Provident Fund-Subscriptions & loan repayments	1,80,76,870	1,73,49,856
N P S Subscription	16,53,501	14,13,801
Profession Tax	4,76,200	4,87,900
LIC - Salary Savings Scheme	25,44,628	24,17,906
Group Insurance Scheme (LIC)	19,17,077	13,02,908
Income Tax deducted at Source	1,25,51,424	1,28,00,467
Housing and other loans	6,40,282	6,20,544
Caution Deposits for Hostel	28,500	28,500
Sundry Creditors	33,22,251	
Recoveries from Contractors towards:		
Income Tax Deducted at Source	7,58,370	8,87,586
Earnest Money Deposits	12,20,500	20,56,998
Security deposits	2,38,522	4,92,274
Others (amounts received for meetings etc.,)		
TIFR - Bombay for conducting US India advanced studies		18,00,000
TOTAL	4,34,28,125	4,16,58,740

PARTICULARS	2014-2015 Non-Plan Rs.	2014-2015 Plan Rs.	2014-2015 Total Rs.	2013-2014 Rs.
SCHEDULE - E				
Recurring Expenditure (Non-Plan and Plan)				
A. Salaries & Allowances:				
Pay	27,67,816	6,65,51,955	6,93,19,771	6,34,62,422
Allowances	58,25,725	8,86,39,788	9,44,65,513	8,55,30,407
Medical Reimbursement	8,41,353	50,81,211	59,22,564	60,02,876
Leave/Home Travel Concession	2,30,346	15,18,397	17,48,743	20,84,409
Leave Salary Encashment - LTC tour	57,467	8,84,071	9,41,538	6,58,304
Contribution towards:				
Provident Fund	39,770	17,46,232	17,86,002	19,87,540
Pension Fund	3,10,865	25,66,020	28,76,885	46,91,409
N P S Contribution		16,53,501	16,53,501	14,13,801
Retirement Fund		28,48,827	28,48,827	86,97,080
SBI Life Insurance - Annual premia		91,800	91,800	
Shortfall in Pension		1,78,51,270	1,78,51,270	1,50,25,628
	1,00,73,342	18,94,33,072	19,95,06,414	18,95,53,876
B. Travelling Expenses		44,64,086	44,64,086	48,90,184
Total (A + B)	1,00,73,342	19,38,97,158	20,39,70,500	19,44,44,060
C. General Expenses				
Wages		5,66,225	5,66,225	3,38,500
Honoraria & Profession fees		18,70,472	18,70,472	16,07,635
Printing Stationery & binding of Scientific journals		12,55,072	12,55,072	14,32,676
Telephone and Communication charges		25,31,681	25,31,681	30,84,252
Electricity Charges *(incl.Rs.3,56,630/- being outlay on maintenance of generators)*		1,04,59,176	1,04,59,176	1,01,69,414
Water Charges		6,57,534	6,57,534	4,56,324
Advertisement		1,98,795	1,98,795	69,813
Vehicle Maintenance/Transport		22,55,080	22,55,080	19,77,469
Liveries & Uniforms		2,28,993	2,28,993	2,34,883
Postage & Courier Services		1,36,294	1,36,294	1,86,908
Seminars, Conferences, Colloquia, etc.,		12,57,955	12,57,955	29,62,723
Bank Charges		8,470	8,470	6,840
Amenities		14,59,922	14,59,922	12,23,620
Crèches expenses		2,40,000	2,40,000	2,40,000
Entertainment and Hospitality		3,39,354	3,39,354	2,85,178
Audit Fee		47,191	47,191	47,191
Repairs & Maintenance (incl. Maintenance of Computers)		92,70,442	92,70,442	85,89,790
Campus Maintenance		77,53,650	77,53,650	74,17,815
Payroll processing charges		3,21,631	3,21,631	3,67,639
Carried forward		4,08,57,937	4,08,57,937	4,06,98,670

PARTICULARS	2014-2015			2013-2014
	Non-Plan Rs.	Plan Rs.	Total Rs.	Rs.
Brought forward		4,08,57,937	4,08,57,937	4,06,98,670
Security		72,89,793	72,89,793	69,79,615
Stores & Consumables		2,53,97,612	2,53,97,612	2,05,58,890
Project Working Expenses		66,36,437	66,36,437	41,53,035
Subscription to Scientific Journals & other Publications		75,79,826	75,79,826	1,09,70,469
Ph. D Programme		41,91,188	41,91,188	42,83,058
Pancharatnam Fellowship				96,592
Lease Rent of Land		4,39,172	4,39,172	2,71,092
Corporation Taxes		3,04,018	3,04,018	3,04,018
Freight, etc.,		3,93,200	3,93,200	2,36,596
Conveyance		4,05,707	4,05,707	3,96,698
Inter Institutional Collaboration & Visiting Scientists' expenses		21,70,795	21,70,795	26,23,157
Visiting Students programme		79,87,341	79,87,341	82,31,549
Outreach		1,59,399	1,59,399	6,49,356
Patent Fees		2,32,995	2,32,995	9,65,459
Miscellaneous Expenses		4,77,372	4,77,372	6,14,783
Affiliation Fee for Universities		3,00,000	3,00,000	3,00,000
Advances to Staff (HBA, Vehicle, Festival & Computer advances)	3,04,500		3,04,500	6,89,250
TOTAL - C	3,04,500	10,48,22,792	10,51,27,292	10,30,22,287
GRAND TOTAL (A+B+C)	1,03,77,842	29,87,19,950	30,90,97,792	29,74,66,347

PARTICULARS	2014-2015 Rs.	2013-2014 Rs.
SCHEDULE - F		
Plan Non-Recurring Expenditure		
Capital Equipment	5,22,88,205	6,37,13,246
Buildings, Works and Services	31,58,863	94,60,284
Books	15,64,731	17,41,670
Furniture & Fixture	6,59,164	7,28,996
Vehicle		7,00,133
TOTAL	5,76,70,963	7,63,44,329
SCHEDULE - G		
Expenditure out of Grants/Assistance from other Government Agencies		
a) Ministry of Science & Technology -		
1) Ramanujam Fellowship	12,45,602	
2) Swarna Jayanthi Fellowship		7,38,016
3) Enabling New Sciences- MWA		15,87,091
4) DBT - Ramalingaswami Re-entry Fellowship	18,14,677	1,93,522
5) Indo-Austrian (BMWF) Joint Research	84,421	
b) ISRO - SSO Project		41,06,742
c) IFCPAR Research Project		16,59,095
d) INSA - Fellowship	33,418	3,36,582
e) CSIR - Extra Murual Research project	1,80,000	5,40,000
f) CSIR - Jr. Research Fellowship	98,800	2,56,000
g) Theiss Research Programme	12,80,317	
TOTAL	47,37,235	94,17,048
SCHEDULE - H		
Advance to Suppliers (Net)		
Plan -Non-Recurring	8,93,989	1,52,24,672
TOTAL	8,93,989	1,52,24,672

PARTICULARS	2014-2015 Rs.	2013-2014 Rs.
SCHEDULE - I **Deposits & Other Remittances**		
Remittances of recoveries from staff:		
Provident Fund Subscriptions and Loans	1,80,76,870	1,73,49,856
N P S Subscription	16,53,501	14,13,801
Professional Tax	4,77,900	4,88,150
LIC - Salary Savings Scheme	25,44,628	24,17,906
Group Insurance Scheme	19,18,027	13,02,358
Income Tax Deducted at Source	1,25,51,424	1,28,00,467
Housing and other loans	6,40,282	6,20,544
Caution Deposits for Hostel	27,000	12,000
Sundry Creditors		61.283
Staff/Miscellaneous Advances & Deposits (Net)	5,11,482	18,03,233
TDS Receivable	35,865	512
Remittances/Refunds of recoveries from Contractors:		
Income Tax deducted at Source	7,58,370	9,80,698
Earnest Money Deposits	12,84,294	24,07,709
Security Deposits	2,59,786	3,32,157
Others (amounts received for meetings etc.,)		
TIFR - Bombay		31,549
TIFR - Bombay for conducting US India Advanced Studies		18,00,000
TOTAL	4,07,39,429	4,38,22,223
SCHEDULE - J **Closing Balance**		
Cash at Bank:		
State Bank of India	68,91,783	3,08,397
State Bank of Mysore	4,39,761	28,57,819
Canara Bank	2,16,177	5,15,923
Union Bank of India	82,141	4,14,449
Central Bank of India	18,777	17,695
Stamps on hand	19,093	285
TOTAL	76,67,732	41,14,568

As per our Report 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 [illegible]

Place : Bangalore
Date : August 18, 2015

RAMAN RESEARCH INSTITUTE
BANGALORE

SCHEDULE: - 17

SIGNIFICANT ACCOUNTING POLICIES AND NOTES ON ACCOUNTS FOR THE YEAR ENDED 31.03.2015

A. SIGNIFICANT ACCOUNTING POLICIES:

1. ACCOUNTING CONVENTION:

The Financial Statements are prepared on the basis of Historical cost convention and on the Cash method of accounting. The guidelines given by the Government of India for drawing Financial Statements for central autonomous bodies have been adopted, to the extent that they are applicable.

2. FIXED ASSETS:

Fixed assets are stated at cost of acquisition less depreciation.

3. DEPRECIATION:

Depreciation is provided on **Straight Line Method** (at the following rates viz., Buildings @ 1.63% , Capital Equipment, Canteen Infrastructure & Books @ 4.75% Computer & Periperals @ 16.21% and Vehicle @ 9.50%).The amount of depreciation has been debited to capital fund and not to the Income & Expenditure Account, since the amount spent on non recurring expenditure out of the grant received every year from DST has been credited to the capital fund, as stated in Accounting policy No.5 'Government Grants'

4. INVENTORY:

Stocks on hand such as spares, materials, consumables are valued at cost.

5. GOVERNMENT GRANTS:

Government grants received from DST are accounted on realization basis and the same have been separately shown under Plan and Non-Plan in the Annual accounts of the Institute. Out of the total Plan grant amount received, an amount equal to the amount of non recurring expenditure incurred during the year has been directly credited to the Capital Fund A/c, the balance of Plan grants is reckoned as Income and shown in Income & Expenditure Account.

6. FOREIGN CURRENCY TRANSACTIONS:

Transactions denominated in foreign currency are accounted at the exchange rates prevailing at the dates of the transaction.

7. RETIREMENT BENEFITS:

- Institute's Contribution to Provident Fund and Pension Fund are charged to Income and Expenditure Account of the Institute. Apart from this, any deficit in the Provident Fund and Pension Fund amount is being borne and provided for in the accounts of the Institute. There has not been any deficit in Provident Fund.

B.NOTES ON ACCOUNTS

a). CURRENT ASSETS, ADVANCES AND DEPOSITS:

In the opinion of the Management, the Current Assets, Advances and Deposits have a value on realization in the ordinary course of activities, equal at least to the aggregate amount shown in the Balance Sheet.

b) EMPLOYEES RETIREMENT BENEFITS:

Institute's Contribution for the years payable to Provident Funds (CPF & GPF) are charged to the Income and Expenditure Account of the Institute

I. As prescribed by the Govt. of India, the Institute has subscribed to Funds/Insurance Policies with the SBI Life Insurance, for quantifiable liabilities of service benefits viz., Gratuity, Leave Encashment.

II. The Institute also took a Fund/Policy for commutable portion of the Pension with the SBI Life Insurance.

III. The amounts standing to the credit of three policies are held by the Institute in a fiduciary capacity on behalf of the employees and hence the balance in these funds is disclosed as contra items in Balance Sheet. The interest earned on these funds is ploughed back to the funds and the claims are met out of these funds.

IV. In pursuance of the directions of the Council, the amount representing the Institute's contribution to the Contributory Provident Fund in respect of eligible senior scientific and technical staff who are on contracts renewal to be covered by GPF on their exercising due option is continued to be transferred to GPF (Pension) corpus, the income on which is applied to meet part of the Pension liability, and only the deficit is met out of grant - in - aid.

C. ADVANCE FOR PURCAHSE OF LAND:

The Institute has paid Rs.8,89,61,800/- to M/s. H M T Ltd., being the full valueforthe land vide agreement dated 13th March 2009. An amount of Rs.1,00,00,000/- has been earmarked for registration as same which is awaited for a No objection forms from Government of India. As per the

Memorandum of Understanding with the Indian Academy of Sciences a portion of this land is earmarked for the Academy. The Academy has remitted to the Institute an amount of Rs.1,00,00,000/- as an on account remittance which is reflected under Schedule 5 Sundry Creditors. The Chairman and Managing Director, HMT Limited has assured the Institute that they are in the processing of expediting.

D. Figures pertaining to the previous year have been regrouped / reclassified to suit the current years classification.

E. Contingent Liabilities – Rs. Nil

F. Figures have been rounded off to the nearest rupee.

Vide our report of even date,
for **M/s. G.R. VENKATANARAYANA**
Chartered Accountant
FRN 004616S

C.S.R. MURTHY
Administrative Officer

RAVI SUBRAHMANYAN
Director

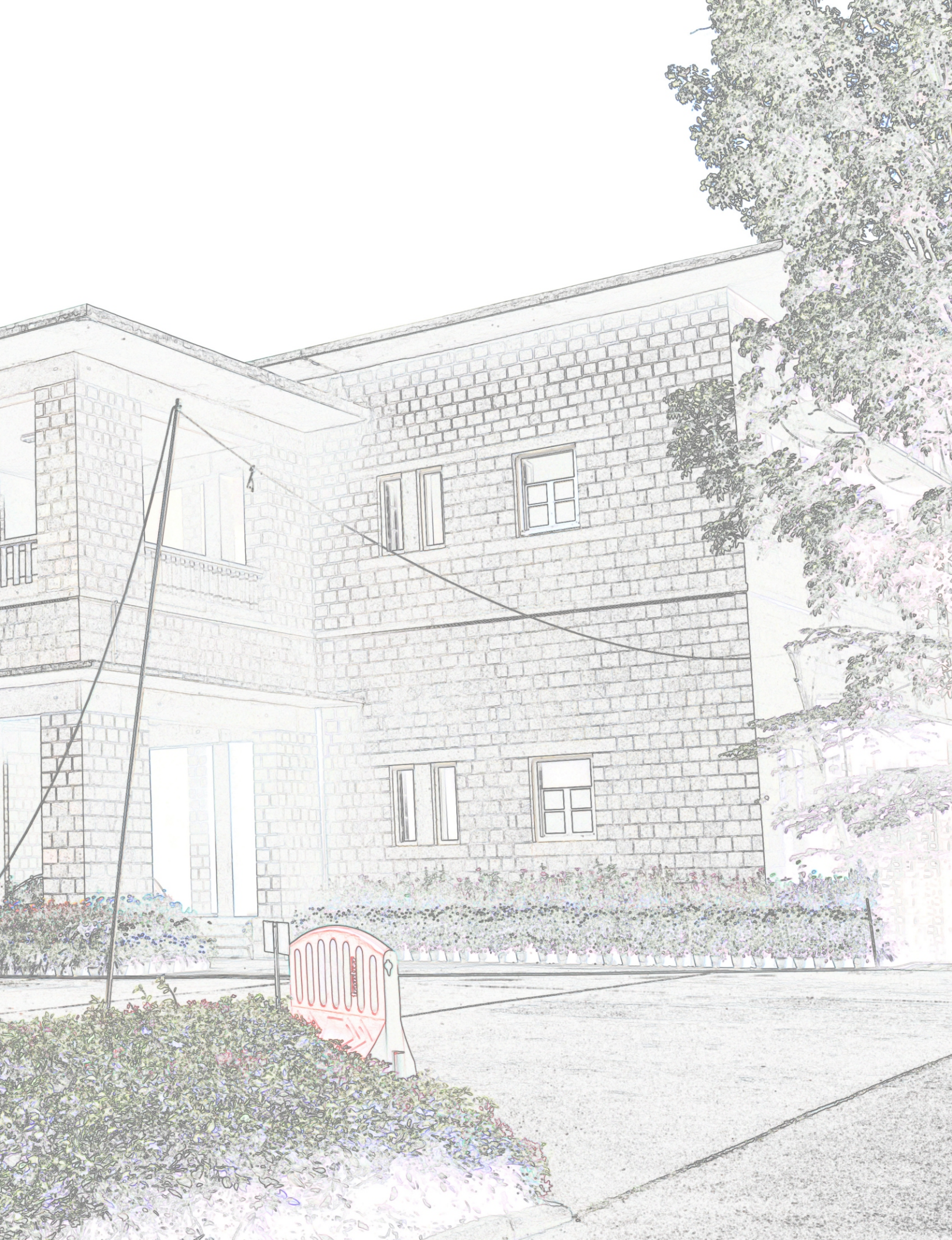
G.R. VENKATANARAYANA
Partner
M No.018067

M/s. G.R. VENKATANARAYANA
Chartered Accountants
618, 75th Cross. 6th Block
Rajajinagar. BANGALORE-560 010

Place : Bangalore

Date: 18th August 2015







"The true wealth of a nation consists not in the stored- up gold but in the intellectual and physical strength of its people."