RAMAN RESEARCH INSTITUTE

Annual Report 2019 - 2020

Contents

From the Director

As in the previous years, the Annual Report is a terse account of the main scientific activities of the Institute. The Annual Report gives the collaborative scientific work conducted at the Institute during the past year, list of publications resulting from this research, seminars and colloquia held and of the PhD degrees awarded during the period 1 April 2019 to 31 March 2020. It also lists the visitors to the Institute - 103 of them from different parts of the world during this period.

The collaborative scientific work covered in the Report and the list of visitors indicate the extent of national and international interactions of the Institute. The list of RRI colloquia given by members of the Institute, by those from the neighboring institutions, and by the visitors at the Institute clearly reflect the breadth of the areas covered.

Seven PhD degrees were awarded to the students of the Institute and ten have submitted their theses during the year. Research papers published in refereed journals and in conference proceedings for the same period counted 129 and 4 respectively, apart from book chapters, and popular science articles. Judging from the impact factors of the journal where their research work was published/accepted for publication, the publication record for the period under review has been very impressive indeed.

V.A.Raghunathan
30 September 2020

RRI at a Glance

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

History

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

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

Administration

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

Mission

The mandate of the Institute is primarily research in basic sciences that advances the knowledge of mankind by creating new knowledge, secondly communicating this knowledge to the next generation thus empowering them with higher learning and scientific temper, and thirdly maintaining an institution of higher learning where academic culture and scientific temper are promoted. The research conducted at the Institute continually advances knowledge base via an improved understanding of the fundamental laws and behaviour of nature spanning from sub-atomic to cosmological length scales thereby laying the basic foundation for advancement of science and its component benefits to society. More importantly, RRI strives to engender quality research manpower through its vibrant Post-doctoral, Doctoral, Research Assistantship and Visiting Student programmes.

Director

The director of the Raman Research Institute is Ravi Subrahmanyan.

Location

RRI is located on a 20-acre site in Bengaluru. The verdant campus with a mix of manicured landscapes and patches of wilderness provides a serene environment away from the hustle and bustle of the developing metropolis beyond its walls, perfectly suited for the creative research and higher learning conducted within.

Research Areas

The research in basic sciences is today in selected areas of Astronomy and Astrophysics, Light and Matter Physics, Soft Condensed Matter Physics, and Theoretical Physics. The research work includes Physics in Biology, Soft Matter Chemistry, Quantum Information, Computing and Communications.

Research Laboratories

- X-ray Astronomy Laboratory
- Molecular Astronomy Laboratory
- Cosmological Recombination & Reionization Laboratory
- Sky Watch Array Network
- Light-Matter Interactions
- Laser Cooling & Quantum Optics
- Ultrafast and Nonlinear Optics
- Quantum Information & Computing
- Quantum Interactions
- Quantum Mixtures Laboratory
- Phase Transitions & Electro-optics
- Rheology and Light Scattering
- Microscopy and Scattering
- Biophysics
- Chemistry
- Electrochemistry and Surface Science

- Microscopy and Dielectric Spectroscopy
- Nanoscale Physics of Soft and Living Matter
- Soft and Adaptive Materials Laboratory
- Brain Computer Interface

Research Facilities

- **Soft Matter Measurement Laboratories**
  - Analytical Physical Measurement
  - X-ray Diffraction
  - Scanning Electron Microscopy
  - Atomic Force Microscopy
  - Nuclear Magnetic Resonance Imaging
  - Micro-Raman Spectroscopy
  - Magnetic Studies Lab
  - Photophysical Studies Lab

- **Mechanical Engineering Services**
  - Mechanical Workshop
  - Sheet metal, paint and carpentry facility

- **Electronics Engineering Group**
- **Gauribidanur Field Station**
- **Library**
- **Computer Group**
- **Infrastructure**
  - Guest House
  - Canteen
  - Clinic
  - Sports facilities
  - Crèche

Education

RRI offers the following programmes for advanced learning and knowledge communication in basic sciences, including theoretical and experimental methods and skills.

- PhD Programme
- Postdoctoral Fellowships
- Pancharatnam Fellowships
- Visiting Students Programme
- Research Assistant 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, and extra-mural grants.

Council

Prof. A.K. Sood, *Chairman*
Year of Science Professor, Department of Physics, Indian Institute of Science, Bengaluru 560012.

Dr. K. Kasturirangan
Honorable Distinguished Advisor, Indian Space Research Organisation, Bengaluru 560231.
Emeritus Professor, National Institute of Advanced Studies, Bengaluru 560012.
Chancellor, Central University of Rajasthan, Dist-Ajmer, Rajasthan 305817.
Chairperson, NIIT University, Rajasthan 301705.

Prof. Ashutosh Sharma
Secretary, Department of Science & Technology, Ministry of Science & Technology, New Delhi 110016.

Shri B. Anand
Additional Secretary & Financial Advisor, Department of Science & Technology, Ministry of Science & Technology
Government of India, New Delhi 110016.

Prof. R. Rajaraman
Emeritus Professor, Theoretical Physics, School of Physical Sciences, Jawaharlal Nehru University, New Delhi 110067.

Prof. Vijay Bhatkar
Chancellor, Nalanda University, Chairman, ETH Research Lab.
National President, Vijnan Bharati, Bavdhan, Off Mumbai-Bengaluru Bypass, Pune 411021.

Prof. H.S. Mani
Adjunct Professor, Chennai Mathematical Institute, H1, SIPCOT IT Park, Kelambakkam, Siruseri, Tamil Nadu 603103.

Prof. Ravi Subrahmanyan
Director, Raman Research Institute (Ex-officio member) Bengaluru 560 080.

Finance Committee

Prof A.K. Sood, *Chairman*
Year of Science Professor, Department of Physics, Indian Institute of Science, Bengaluru 560012.

Shri B. Anand
Additional Secretary & Financial Advisor, Department of Science & Technology, Ministry of Science & Technology
Government of India, New Delhi 110016

Prof. H.S. Mani
Adjunct Professor, Chennai Mathematical Institute, H1, SIPCOT IT Park, Kelambakkam, Siruseri, Tamil Nadu 603103.

Prof. Ravi Subrahmanyan
Director, Raman Research Institute (Ex-officio member) Bengaluru 560 080.

Academic Committee

Prof. Ravi Subrahmanyan, *Chairman*
Director
Raman Research Institute
C.V.Raman Avenue, Sadashivanagar
Bengaluru 560 080.

Prof. Jayant K. Tripathi
School of Environmental Sciences
Jawaharlal Nehru University
New Delhi 110 067.

Prof. Satyabrata Patnaik
School of Physical Sciences
Jawaharlal Nehru University
New Delhi 110 067.

Prof. Tarun Deep Saini
Department of Physics
Indian Institute of Science
Bengaluru 560 012.

Prof. Abhishek Dhar
International Centre for Theoretical Sciences
No.151, Shivakote, Hesaraghatta Hobli
Bengaluru North 560089.

Dr. Vikram Rana
Astronomy & Astrophysics Group
Raman Research Institute
C.V. Raman Avenue, Sadashivanagar
Bengaluru 560 080.

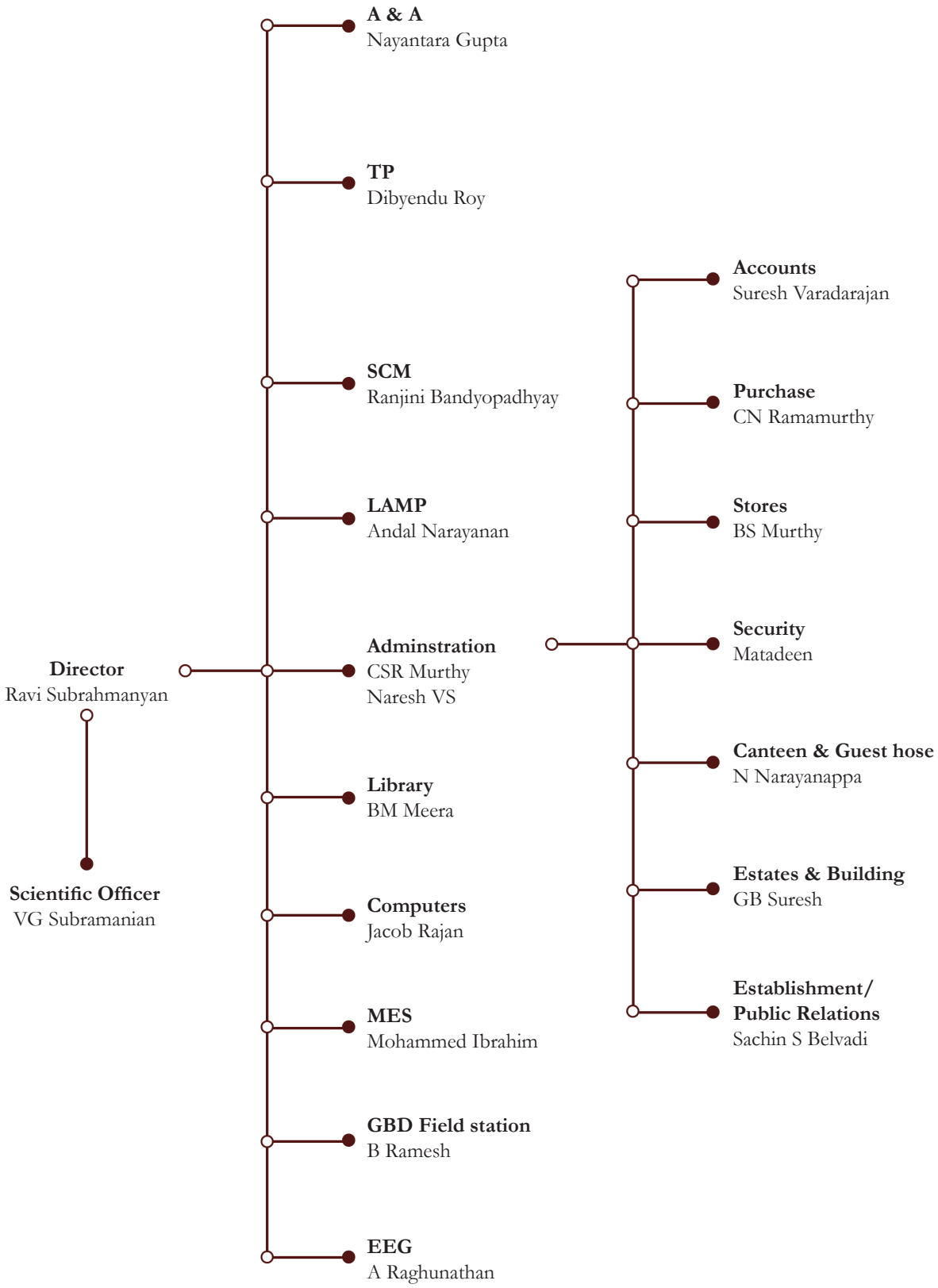
Prof. V.A. Raghunathan
Soft Condensed Matter Group
Raman Research Institute
C.V.Raman Avenue, Sadashivanagar
Bengaluru 560 080.

Prof. Satish Chandra Garkoti, *Special Invitee*
Rector – II, Jawaharlal Nehru University
New Delhi 110 067.

Mr. C.S.R. Murthy (till 31.12.2019), *Secretary*
Administrative Officer
Raman Research Institute
C.V.Raman Avenue, Sadashivanagar
Bengaluru 560 080.

Mr.Naresh V.S. (from 01.01.2020), *Secretary*
Administrative Officer (i/c)
Raman Research Institute
C.V.Raman Avenue, Sadashivanagar
Bengaluru 560 080.

Organisation



RRI Science Forum
Gautam Soni, Andal Narayanan, Nayantara Gupta

Colloquia
Joseph Samuel (Chairperson), N Udaya Shankar, KS Dwarakanath, R Pratibha, Yashodhan Hatwalne

Hostel Wardens
Shiv Sethi, Arun Roy, B Ramesh, Urbasi Sinha

Admissions Coordinators
Vikram Rana, Sayantan Majumdar (from 28.8.2019), Saptarishi Chaudhuri (till 27.8.2019)

Students Academic Affairs Committee
Sadiq Rangwala (Chairperson from 4.6.2019), VA Raghunathan (till 3.6.2019), Pramod Pullarkat, Shiv Sethi, Sumati Surya, Reji Philip (from 5.7.2019)

In-House meeting
PhD students – 3rd year

Joint Astronomy Programme Representative of RRI
B Ramesh

Complaints Committee
Srivani (Chairperson), BM Meera, CSR Murthy (till 31.12.2019), Mamatha Bai R

Overseas Travel Committee
Biswajit Paul (Chairperson), Reji Philip, Supurna Sinha

Evaluation Committee
VA Raghunathan (Chairperson from 4.6.2019), Sumati Surya, Biman Nath,, Sadiq Rangwala, Ranjini Bandyopadhyay (from 24.6.2019), KS Dwarakanath (till 3.6.2019)

Coordinators of Visiting Students Programme
CSR Murthy(till 31.12.2019), NareshVS (from 1.1.2020)

Library Committee
BM Meera (Chairperson), Supurna Sinha, Nayantara Gupta, Andal Narayanan, Ranjini Bandyopadhyay

RRI Official Language Implementation Committee
CSR Murthy (Chairperson till 31.12.2019), Naresh VS (Chairperson from 1.1.2020), Suresh Varadarajan, R Ramesh, CN Ramamurthy, B Srinivasamurthy, BM Meera, K Radhakrishna, V Vidyamani, Harini Kumari, Mamatha Bai R, Jacob Rajan

Prelude

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

History

RRI was founded in 1948 by the Indian physicist and Nobel Laureate, Sir C V Raman, on land that had been gifted to him by the Government of Mysore to continue his studies and basic research after he retired from the Indian Institute of Science. Professor Raman served as its director carrying on his research, which was funded personally by him and with donations from private sources. After the Professor's demise in 1970, a public charitable trust was created - the Raman Research Institute Trust – and the lands, buildings, laboratories, instruments, and all other movable and immovable properties were transferred to the RRI Trust. The function of the RRI Trust was to maintain, conduct and sustain RRI.

Administrative set-up

The Raman Research Institute is now an autonomous research institute engaged in research in basic sciences. In 1972, RRI was restructured to become an aided autonomous research institute receiving funds from the Department of Science and Technology of the Government of India. A set of Regulations and Bye-Laws were framed for its administration and management. The Governing Council, which is the executive body of the Institute with oversight of the administration and management of the Institute, sets policies towards the mandated goal of conducting research in basic sciences that is qualitatively outstanding, thus giving the country a respected standing amongst the international intelligentsia. Reports of research outcomes and performance are peer reviewed by International experts in the respective fields and the research and assessments are reported at Council Meetings and also made available to the Government of India in the form of Annual Reports. The members of the council include personalities with substantial research and science management experience as well as representatives from the Department of Science & Technology, Government of India.

Objectives of RRI

The Institute carries out the mandate as defined by the Governing Council and RRI Trust to be basic research with focus in niche fields of

1. Astronomy & Astrophysics including theoretical astrophysics, observational astronomy, and experimental Radio and X-ray astronomy,

2. Light & Matter Physics including cold atoms, ions, molecules, quantum communications and computing, and intense laser produced plasma,

3. Soft Condensed matter including research in liquid crystals, nano-composites, colloids, chemistry and biological physics, and

4. Theoretical Physics including General Relativity, Foundational quantum mechanics, soft matter physics, and classical and quantum Statistical Mechanics and Gravity.

The goal of the research in basic sciences is to advance the knowledge of mankind by creating new knowledge, communicating this knowledge to the youth thus empowering them with higher level skills, maintain an institution of higher learning where academic culture and scientific temper are promoted, thus giving the country a respected standing amongst international peers.

The research conducted at the Institute continually advances knowledge base via an improved understanding of the fundamental laws and behavior of nature spanning from sub-atomic to cosmological length scales thereby laying the basic foundation for advancement of science and its component benefits to society. More importantly, RRI strives to engender quality research manpower in the above-mentioned areas through its vibrant Postdoctoral, Doctoral, Research Assistantship and Visiting Student programs. The work quality and quantity is evidenced by documented research reports provided annually to the Department of Science & Technology, Government of India.

The work of the Institute is with three objectives:

(i) KNOWLEDGE CREATION, or engagement in the furtherance of the frontiers of the knowledge of humankind. This research activity includes theoretical work exploring foundational mathematics with the aim of

arriving at frameworks within which phenomena may be described and hence understood, devising and developing theory of phenomena, and theoretical models for phenomena. Knowledge creation includes observational and experimental activity that tests alternate models and hypotheses, and computational activity that explores consequences of physics theories in complex behaviors. All of these may be individual pursuits, collective efforts of members of the Institute and often in collaboration worldwide with individuals and groups that have complementary expertise, and sometimes as national and international science projects that often bring substantial resources together towards solving key problems that require such collective efforts.

(ii) KNOWLEDGE COMMUNICATION, or engagement in empowering the next generation. The Institute has a PhD program that involves selection of appropriate candidates, guiding them through advanced learning and technical skills in preparation for research in frontier unsolved problems, then proving opportunities for supervised research work leading to a doctorate degree, which is the basic qualification for a research career. The Institute has a 2-tier Postdoctoral program that provides 3-year research experience - both supervised and independent - for outstanding PhDs. This provides guided transition from supervised to independent research. The Research Assistantship program and the Visiting Students program of the Institute invite post-graduate, undergraduate and even motivated high school students to spend weeks, months and up to 2 years participating in the research, experiencing research methods and pathways, so that they may find their passion and be motivated and empowered by the involvement to embark on careers in research in basic science. For details of the educational and research experience opportunities provided by the Institute the reader may visit the academic programmes section of this report.

(iii) PROMOTING ACADEMIC TRADITIONS, by engaging in activities that nurture scholarship, foster academic ambience and activities in the Institute, and facilitate scientific and academic management via participation in institutional, national and international boards that manage scientific planning and projects, thus promoting the cause of science, higher learning and research. The Institute holds specialized seminars in the different disciplines of higher learning that are intended for the specialists, colloquia that provide a wider audience an introduction and review of fields, a regular Science Forum where recent results in emerging areas of research are introduced and discussed in an inclusive manner. A complete list of these academic activities is provided in the appendices.

Astronomy and Astrophysics

Overview

From the beginning humankind has looked up at the sky with a sense of curiosity. It is no wonder that astronomy is one of the oldest of natural sciences. The field of Astronomy and Astrophysics pertains to a detailed study of the physical, chemical and dynamic properties of celestial objects. The research conducted in the AA group at RRI can be broadly classified into four areas:

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

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

(c) *Experimental Astronomy* involves the *design, construction and operation of telescopes* for very specific purposes to address key unsolved problems, and are strategically located around the world and in space.

(d) *Algorithms & Signal processing* where a variety of methods and modelling are employed to amplify and or isolate the required astronomy signal from other foregrounds, backgrounds and unwanted interference and confusion.

Focus 2019-20

Theoretical Astrophysics and Cosmology

The universe that we inhabit is vast beyond comprehension, complex, constantly expanding and is populated by myriad astronomical entities. The universe is populated by stars, galaxies, galaxy clusters, also objects emitting high-energy particles like Blazars and Gamma Ray Bursts. The space between stars, galaxies, galaxy clusters and the roughly spherical region that extends out from a galaxy is permeated by diffuse gas and dust. These are known as interstellar medium, intergalactic medium, intracluster medium and

circumgalactic medium respectively. The Universe is thus a very vibrant place with constant interactions and various dynamic processes that shape their evolution and in turn the evolution of the universe as a whole. By studying these cosmic entities, their evolution and physical properties, astrophysicists, and on a much larger scale, cosmologists try to understand the evolution of the universe and its workings within the framework of the known laws of physics and chemistry. Analytical modelling and/or numerical simulations shed light on these processes and add to the knowledge of our understanding of the Universe. A brief description of the research activities in Theoretical Astrophysics and Cosmology during 2019-20 is given below. For a detailed description of the research, the reader is invited to visit the "Knowledge Creation: Astronomy and Astrophysics" section of this Annual Report.

Interstellar Medium

With collaborators Eugene Vasiliev and Yuri Shchekinov, Biman Nath has been studying the optical and IR lines whose properties could be used as a diagnostic for measuring the supermassive black hole mass, the gas mass in the galaxy and the stellar mass. Their study resulted in the selection of a few nebular lines, whose ratio may be useful for estimating the three important masses mentioned above.

Galactic Outflows

With detailed realistic modeling Biman Nath, Siddhartha Gupta and collaborators Prateek Sharma and David Eichler have shown that wind termination shock contributes to at least a quarter of the total galactic cosmic ray production in superbubbles with the rest coming from supernova remnants. With his PhD students Ranita Jana and Siddhartha Gupta, Biman Nath studied the role of cosmic rays in galactic outflows, with detailed hydrodynamical 2-fluid simulations, and corrected the mistaken lore that cosmic rays dynamically affect outflows. With a Masters student Pushpita Das, Biman Nath has done Monte-Carlo simulation of superbubbles in a disc galaxy and compared the size distribution with that observed in THINGS survey. In this work they have included the effects of cooling and non-thermal pressure in ISM, using hydrodynamical simulations of bubbles, and compared them with observations.

Galactic Structure and Stellar Dynamics

The spiral patterns of disc galaxies like the Milky Way are some of the most beautiful structures formed by stars and gas in the Universe. They are density enhancements, driving disc evolution through new star formation and angular momentum transport. The density-wave theory of the 1960s failed to produce long-lived spiral patterns because the wave is absorbed at Lindblad resonances. Further progress came through careful numerical experiments, which suggested that spiral structure could arise from transient modes that create conditions conducive for their regeneration. During the past year, S. Sridhar has developed a first-principles theory of this phenomenon. A transient spiral mode leaves behind "resonant scars" in phase space. Dissipation is suppressed within these scars, so they act as filters of the spectrum of noise-generated modes, promoting the renewal of a few select modes. Relic scars sustained by a galaxy disc, due to past tidal interaction with a passing companion, may still be active enablers of two-armed "grand design" spiral patterns.

High Energy Astrophysics

The High Energy Astrophysics group at RRI is involved in modelling the propagation of Galactic and extragalactic cosmic rays with Monte Carlo simulations. They do multi-wavelength modelling of Galactic and extragalactic gamma ray sources to reveal the underlying physics of high-energy particle production within cosmic accelerators.

Using a lepto-hadronic model, Nayantara Gupta and her PhD student Saikat Das along with collaborator Soebur Razzaque have explained the observed multiwavelength photon spectrum of a number of BL Lacertae (BL Lacs) objects detected at very high energy and have shown that the ultrahigh-energy cosmic ray interactions could be the origin of the very high energy gamma-rays from these objects. The recent data on cosmic ray positron flux measured near the Earth has revealed that it rises with energy which cannot be explained by interactions of cosmic rays with interstellar hydrogen gas. Agnibha De Sarkar, Sayan Biswas and Nayantara Gupta have shown that the positron excess could be accounted for by including the secondary positrons produced in gaint molecular clouds via interactions of cosmic rays with molecular hydrogen. Analysis of the long term light curve of a balzar source with data from Fermi LAT detector has enabled Nayantara Gupta and her PhD students Avik Kumar Das and Raj Prince identify five flares and one quiescent state. This study also provides mechanisms that could explain the light curves of select flaring peaks. Another work during the past year by Nayantara Gupta, her PhD student Saikat Das and collaborator Seobur Razzaque has been on modelling the spectrum and composition of ultrahigh-energy cosmic rays. Two populations of extragalactic sources with one population accelerating protons while the other population accelerates Helium, Nitrogen, Silicon and Iron, was found

to provide a good fit to the spectrum and composition data of ultrahigh energy cosmic rays. Lepto-hadronic modelling of the multi-wavelength data from a blazar that was in a flaring state during neutrino detection, by Nayantara Gupta and collaborators has led to estimations of jet luminosities during the neutrino phase of that blazar. Finally, during the past year, the temporal and spectral variability of two flares of a blazar in early 2010 were studied and modelled with a two zone emission model by Nayantara Gupta and collaborators Sonal R. Patel and Debanjan Bose.

Cosmology

Studies on the formation of the first stellar size black holes in the Universe by considering the hyperfine line of 3He II as the main observable by Shiv Sethi and collaborators Eugene Vasiliev and Yuri Schehinov has provided estimates for the brightness temperatures and structural information in the region surrounding the black hole. In another work, the cosmological implications of stable charged particles as cold dark matter in the universe was considered by Shiv Sethi and A P Gautham, a visiting student at RRI by studying, computing and comparing cosmological observables for three different models, with Plank CMB data. Considering observations of the cross-correlation of the HI 21-cm signal and the Lyman- forest with various instruments and surveys has enabled Anjan Sarkar and collaborators Ashis Pal and Tapomoy Sarkar to place constraints on the cross Warm Dark Matter (WDM) power spectrum and on the WDM mass. In another work, Anjan Sarkar and collaborators have made predictions for measuring the Epoch of Reionization 21cm signal multi-frequency angular spectrum using the Square Kilometer Array-Low.

Observational Astronomy

It would come as a surprise to many if you tell them that what the human eye sees of the night sky is just a very small portion of what is really coming to us from the heavens above. The reason being that the human eye is sensitive to just one small portion of the much larger panorama called the electromagnetic spectrum, which includes gamma rays, X-rays, ultraviolet, microwave and radio waves. On a fundamental level the above different forms of radiation are all the same, the difference lies in the frequency and wavelengths of the electromagnetic signal. The universe talks to us over the entire electromagnetic spectrum and the innate curiosity of the human mind would want to devise ways to listen. Astronomers have in fact built specialized telescopes designed to "see" in different frequency bands of radiation. RRI has been involved in designing and constructing Radio and X-ray telescope facilities both nationally and internationally - for example the Murchison Widefield Array (MWA), a precursor to the SKA telescope, which is a megaproject of the nation, and ASTROSAT, a multi institutional collaborative satellite mission launched by ISRO - which they routinely use to study cosmic objects of interest.

Radio Astronomy

The carousel model of pulsar emission attributes the phenomenon of subpulse drifting to a set of discrete sparks located very near the stellar surface rotating around the magnetic axis. Studies of frequency dependence of a pulsar's subpulse behaviour using this model has enabled Avinash Deshpande and collaborators S. J. McSweeney, N. D. R. Bhat, S. E. Tremblay and G. Wright to come up with a new method for measuring emission heights for pulsars. The very low-frequency radio sky (below 20 MHz) has not yet been explored adequately mainly because of the Ionospheric cutoff. Avinash Deshpande, Vinutha Chandrashekar, H A Aswathappa along with collaborator Pavan Uttarkar developed a suitable setup and used it to estimate and account for the ionospheric imprint in terms of frequency dependent absorption and its variation in time. In collaboration with Dr. Nimesh Patel, current efforts by Mohit Sinha and Ramesh Balasubramanyan are towards studying the interaction between the fast and slow winds of the Egg Nebula (AFGL 2688; CRL 2688), a well-known proto- planetary nebula, in order to compare the molecular observations with a binary-induced spiral shell model. A method to derive the dynamical mass of face-on galaxy disks using their neutral hydrogen velocity dispersion was developed during the past year by K S Dwarakanath and collaborators Mousumi Das, Stacy S. McGaugh, Roger Ianjamasimanana and James Schombert. Application of this method to a sample set of galaxies has provided insights that are important for explaining normal and dark matter mass distribution in these galaxies. Detailed analysis of star formation properties of galaxies in a post-merger cluster system by Kshitija Kelkar, K S Dwarakanath and collaborators Bianca M. Poggianti, Alessia Moretti, Rogerio Monteiro- Oliveira, Rubens Machado, Gastao Lima-Neto, Jacopo Fritz, Benedetta Vulcani, Marco Gullieuszik and Daniela Bettoni has revealed that it contains a population of massive (M(stars) greater than 10M(Sun)) blue regular star-forming spirals in regions of maximum merger shock influence but exhibiting star formation rates similar to those in relaxed clusters at similar epoch and low-mass (M(star) less than 10M(Sun)) late-type blue post-star burst galaxies which could either be formed as a result of rapid quenching of low-mass spirals following the shock-induced star formation or due to the intense surge in the intracluster medium pressures at the beginning of the merger. Observations of the redshifted HI 21cm line in a

large sample of star-forming galaxies by K S Dwarakanath, Shiv Sethi and collaborators Aditya Chowdhury, Nissim Kanekar and Jayaram Chengalur has allowed them to measure the average HI mass of star-forming galaxies at a redshift z approximately equal to 1 and provide implications for cosmic star-formation rates after the epoch of galaxy assembly. K. S. Dwarakanath and collaborators Sumana Nandi and Mousumi Das have studied radio observations of ultraluminous infrared galaxies (ULIRGs) using the Giant Metrewave Radio Telescope (GMRT) combined with archival multifrequency observations and have concluded that although most ULIRGs do not show kpc scale extended radio emission associated with nuclear activity, their radio spectral energy distributions do show signatures of young radio galaxies. With collaborator Andre Offringa, Jishnu Nambissan has measured the power spectra of the 21cm signal using the LOFAR instrument and analysed data from observations of one the fields close to the north celestial pole (NCP).

X-ray Astronomy

Compact X-ray binaries are composed of a compact object, a neutron star or a black hole and a companion 'normal' star. The intense gravitation field of the neutron star causes matter from the companion star to accrete onto the neutron star, producing X-rays. X-ray astronomy is a powerful tool to study such objects. A plethora of information about system parameters like magnetic field geometry and strength, chemical composition of the surrounding medium and dynamics like orbital period and radius evolution of X-ray binaries, structural evolution of the accretion disk and its time scales, and structure in the stellar winds can be obtained by a careful analysis of the X-ray output from compact X-ray binaries. Research is also towards studying Cataclysmic Variable systems and Ultra-luminous X-ray sources using data from various X-ray observatories. A brief overview of various aspects of X-ray sources investigated by RRI astronomers during 2019-20 is given below.

Broadband spectral-timing analysis and a detailed study and fitting of the spectrum from the X-ray binary SMC X-1 by Biswajit Paul and collaborators Pragati Pradhan and Chandreyee Maitra has led to the suggestion that the super-orbital modulation is not caused by absorption in precessing warped accretion disc alone but also due to intrinsic changes in X-rays emanating from the neutron star at different super-orbital states. This study also provided estimates for the magnetic field strength of the neutron star. Results from investigations of a low intensity phase in the orbital profile of an high mass X-ray binary by Biswajit Paul, his PhD student Sanhita Kabiraj and collaborator Nazma Islam have indicated that the low intensity state might not be an eclipse as previously thought but absorption in the stellar corona. Recent efforts by Biswajit Paul and collaborators Pragati Pradhan, Enrico Bozzo, Antonis Manousakis and Carlo Ferringo was towards investigating the clumpy wind accretion from a classical supergiant X-ray binary and comparing it with similar studies for Supergaint fast X-ray transients. Using simultaneous data from X-ray observatories, Vikram Rana and collaborators Anirban Dutta and Koji Mukai have studied the change in geometry and properties like temperature and composition of the accretion disc during the outburst and quiescent phases of a dwarf nova. Studies of an ultraluminous X-ray source by Vikram Rana his PhD student Tanuman Ghosh and collaborator Dominic Woltan has enabled them to understand disk geometry and emission dynamics from that particular source.

Experimental Astronomy

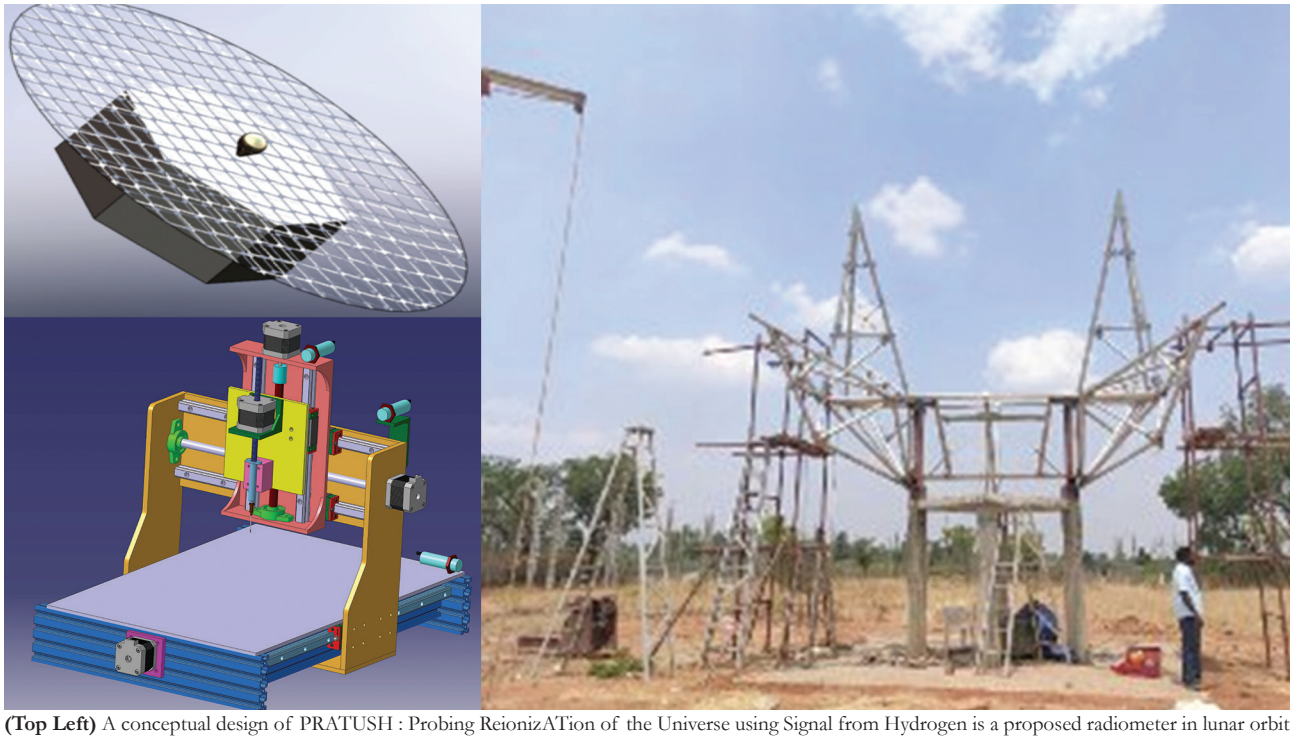
Apart from carrying out observational astronomy with facilities, RRI astronomers do in fact built specialized telescopes designed to "see" in different frequency bands of radiation with focus on specific unsolved problems. The unrelenting quest for pushing the frontiers of knowledge about the observable universe and the need to see hitherto hidden regions of space has fueled the need for better, efficient and sensitive telescopes and associated receivers and algorithms. AA research at RRI over the past year has focused on both these aspects and RRI astronomers and engineers have been involved in designing and constructing Radio and X-ray telescopes both nationally and internationally: the X-Ray polarimeter payload called POLIX, poised to be the first dedicated X-ray polarimeter mission in space, a precision radiometer called SARAS operating in the 40-230 MHz radio band dedicated to detecting spectral distortions in the cosmic radio background, PRATUSH, a proposed radiometer in lunar orbit that aims to detect the redshifted 21-cm signal from Cosmic Dawn of our Universe, an Efficient Linear Array Imager, a Supernova Search Engine, both operating at Radio wavelengths, and the Sky Watch Array Network (SWAN) that primarily aims at exploring the transient radio sky.

Mayuri S Rao, Saurabh Singh, Jishnu Nambissan, Ravi Subrahmanyan, Udayashankar N, other members of the CMB distortions lab, Electronics Engineering Group, Mechanical Engineering Services at RRI and international collaborators are associated with different experiments terrestrially and in space that aim to detect the 21-cm signal from neutral hydrogen to better understand the evolution of Universe when the first stars formed. During the past year, progress has been made on developing and optimizing PRATUSH-C3, a precision spectral-radiometer

as a payload on the Chadrayaan-3 mission. Focus has also been on commissioning and deployment of SARAS-3 system, another experiment aimed at detecting the global 21-cm signal. During 2019-20, significant progress has been made towards completion of the Qualification Model (QM) and Flight Model (FM) of POLIX, an Indian X-ray polarimeter to be launched as a payload on ISRO's satellite XPoSat. Biswajit Paul, P. V. Rishin, Vikram Rana, M. R. Golapakrishna, S. Krishnamurthy, Md Ibrahim, M. Hemant, Pooja Verma, Md. Irshad, Harikrishna Sahoo, G. Rajagopala, Nandini Sreeanand, T. S. Mamatha, P. Sandhya, Ashwin Devraj, Abhilash Kulkarni, Varun and many members of Mechanical Engineering Services have made major contributions in developing both the QM and FM. Towards a collaborative effort in developing technology for a hard X-ray telescope, Vikram Rana has designed and developed an automated epoxy dispensing machine for stacking flat glass mirrors using epoxy and precisely machined graphite spacers. The past year saw the Indian SWAN demonstrator system of 7-tiles located presently at the Gauribidanur Field Station made ready for relocation, after successfully incorporating separate beamformer supply and control hardware/software, as well as GPS-disciplined Rubidium frequency standard. Sandeep H, Avinash Kotla, Sandeep K, Charles Paul, and Ramesh B made progress in constructing the ELI telescope with antenna base civil structure and various joint parts being built and installed during the past year.

Algorithms & Signal Processing

Research effort at the Institute is also focused on developing methods and algorithms that would detect the required signal from background or place useful constraints on the parameter space of theoretical models. Assuming entropy functions different from -p.log(p), investigations of maximum entropic probability density distributions (PDFs) by Avinash Deshpande and collaborator Albert Shaji has shown that for -log(p) entropy, the maximum entropic distribution is the Cauchy distribution, relevant as PDF only in certain range of characterizing parameters.



(Top Left) A conceptual design of PRATUSH : Probing ReionizATion of the Universe using Signal from Hydrogen is a proposed radiometer in lunar orbit that will reveal a wealth of information about the first stars and galaxies in our Universe. PRATUSH proposed by members of RRI CMB DISTORTION Lab was funded by ISRO for pre-project studies mode over 2019-2020. **(Bottom Left)** Automated epoxy dispensing machine for stacking flat X-ray mirrors. This effort is towards building a hard X-ray telescope. **(Right)** A view of the Efficient Linear array imager telescope backup structure constructed at the Gauribidanur Field Station.

Light and Matter Physics

Overview

Light and matter interaction is at the heart of how scientists learn about the physical properties of objects ranging in size from that of the universe down to atomic scales. At the Raman Research Institute members of the light and matter physics (LAMP) group are engaged in research on fundamental properties of electromagnetic (EM) waves and on the nature of interaction of EM waves with gaseous neutral atoms, ions, ultra-cold and exotic states of matter. The underlying theme of these studies is to unravel fundamental processes which will qualitatively improve our understanding of the studied phenomena and provide new guiding principles. The knowledge thus gained will help in utilization of these principles both at the fundamental and at the applied level.

Focus 2019-20

Ultra-cold Atoms and Molecules

One major area of research in the LAMP group involves the cooling and trapping of atoms, ions and molecules in order to study interactions between them and with electromagnetic fields at low temperatures.

A recently started activity at RRI is the setting-up of a new state-of-the art experimental system with mixtures of ultra-cold atom clouds. The long-term goal of this lab will be to investigate formation of quantum degenerate polar molecules with tunable, long-range dipolar interactions. An area which such a system will be a very useful tool is to simulate complex condensed matter phenomena in a controllable setup. Towards this, Saptarishi Chaudhuri along with team members Sagar Sutradhar, Shreya Bagchi, Bidyut Bikash Boruah and Sanjukta Roy have focused on developing purpose-built ultra-high vacuum and laser systems. Specifically, they have designed two high-flux atomic beam sources in the form of two-dimensional magneto optical trap (2D-MOT) for K and Na atoms. The past academic year they have installed the ultrahigh vacuum system and obtained ultrahigh vacuum (less than 10-10 mbar) after pumping down. A magnetic transport stage was designed to simultaneously transport the trapped atoms in a moving magnetic trap over a distance of nearly a meter to a connected glass vacuum cell with large optical access and ultra-high vacuum. The design and some aspects of implementation was done entirely using RRI facilities. During the past year Subhajit Bhar, Maheswar Swar, Sanjukta Roy and Saptarishi Chaudhuri undertook studies on quantum diffusion where the diffusion of atoms which are at sub milli-kelvin temperatures were studied when they are suddenly released from a trap potential. This set of measurements were motivated and supported by theory collaborators Supurna Sinha, Urbashi Satpathi and Rafael Sorkin.

Interactions in trapped ultracold gases (atoms, molecules, ions and narrow-band light) in hybrid trap experiments

The question the QuaInt (Quantum Interactions) lab poses is: how do trapped dilute gases of different species and their ions interact with each other? At ultracold temperatures, small changes in energy can make a big difference in the nature of interactions.

Sadiq Rangwala and his group members Amrendra Pandey, Niranjan Myneni, Nishant Joshi along with collaborators R. Vexiau and Olivier Dulieu have calculated the isotope independent $^7Li+-^7Li$ potential energy curves for the electronic ground and first excited states. They calculated the scattering phase shifts and total scattering cross section for the $^7Li+-^7Li$ collision with emphasis on the ultra-low energy domain down to the s-wave regime. Sadiq Rangwala wrote an article for Physics News wherein he introduced the need to study interactions between cold and trapped species of atoms, molecules and ions very carefully for an understanding of quantum many particle systems. Sadiq Rangwala, his PhD student Rahul Sawant and collaborator Sourav Dutta also extended their earlier study on mass ratios of colliding atoms and ions of different species and proved that for ionic masses less than the atomic masses cooling occurs. Further, for cooling of an ion A^+ by the parent atom A, the mechanism of resonant charge exchange (RCE) allows for extremely efficient cooling of the ion A^+.

Precision Atom-Light Interaction and Spectroscopy with room temperature atoms

Precision atom-light interaction and spectroscopy refers to those studies of light matter interaction where resolution in frequency and spatial domains is demonstrated, which far exceed those achieved during a single photon scattering process. It also includes studies where a near non-demolition measurement is carried out to obtain information about the system under study.

Spin noise correlation spectroscopy measurements from ultra cold atoms was carried out as an extension to the earlier spin noise study on thermal atoms by Maheswar Swar, Dibyendu Roy, Subhajit Bhar, Sanjukta Roy and Saptarishi Chaudhuri. While the highlight of the previous research work was the demonstration of high precision magnetometry using spin noise measurements and non-perturbative detection of atomic population in different hyperfine states, by extending the observation in cold atoms, now, they have not only improved upon the magnetometry precision by two orders of magnitude but also demonstrated the potential of using this technique to measure quantum correlations.

For the past few years Andal Narayanan along with her students and collaborators have been experimentally studying an atom-light interaction phenomena where coherent interaction between light and matter takes place. This coherent interaction can be used to eliminate linear absorption, enhance non-linear interaction with very low light intensities, amplify a weak probe beam and send digital signals between very different frequency regimes with very little or no added noise. In the past, several of these effects were realized with dilute atoms interacting with microwave and optical fields. During the past year Andal Narayanan and her PhD students Asha K., Adwaith K. V. and Pradosh K N along with collaborators Barry Sanders and Fabien Bretenaker have demonstrated an amplification of probe optical field by about 7 dB, which is controlled by the phase of the microwave, thus demonstrating phase sensitive coherent amplification of an EM field that is controlled by another EM field that is several orders separated in frequency.

Intense Light - Matter Interactions

The optical response of a material scales linearly with respect to incident radiation. However, when the intensity of the incoming radiation is sufficiently high the material can respond nonlinearly. The study of the interaction of intense light with matter is known as nonlinear optics. Research during the past year has been on studying nanostructured and other materials capable of nonlinearly transmitting light with respect to input intensity. Such materials have variety of applications including optical limiting and saturable absorption. Optical limiters, for example, are materials that can attenuate intense laser pulses by limiting the output fluence to a safe range so that delicate optical instruments, optical sensors and human eyes can be saved from accidental or hostile exposure.

During the past year, members of Reji Philip's Ultrafast and Nonlinear Optics lab at RRI and collaborators studied nonlinear absorption of various materials for applications as optical limiters; results obtained from this study indicate the potential of these materials for application as efficient optical limiters for the safety of human eyes and sensitive optical detectors from accidental exposure to harmful laser radiation. Reji Philip and his group members Pranitha Shankar, Jyothis Thomas, H D Shashikala generated laser induced plasmas from Ag nanoparticles with enhanced X-ray generation capabilities. They irradiated a thin flowing jet (250 μm) of Ag nanoparticle colloidal suspension by using 150 femtosecond, 800 nm laser pulses to form a plasma which emitted bremsstrahlung X-rays of up to 100 keV energy. The flowing jet ensures long-term stability of the plasma source during continuous laser irradiation. A 30-fold enhancement is observed in the X-ray yield in the nanoparticle suspension, compared to that of the precursor salt solution. Reji Philip and collaborator K K Anoop fabricated durable superhydrophilic surfaces by laser induced micro and nanoscale pattering of surfaces. Long-lasting and durable superhydrophilic silicon were obtained by using maskless, compact and cost effective nanosecond laser writing, without the need to employ any chemical post-processing. Potential applications of these surfaces include heat exchangers, biosensors, cell adhesives and self-cleaning solar cells.

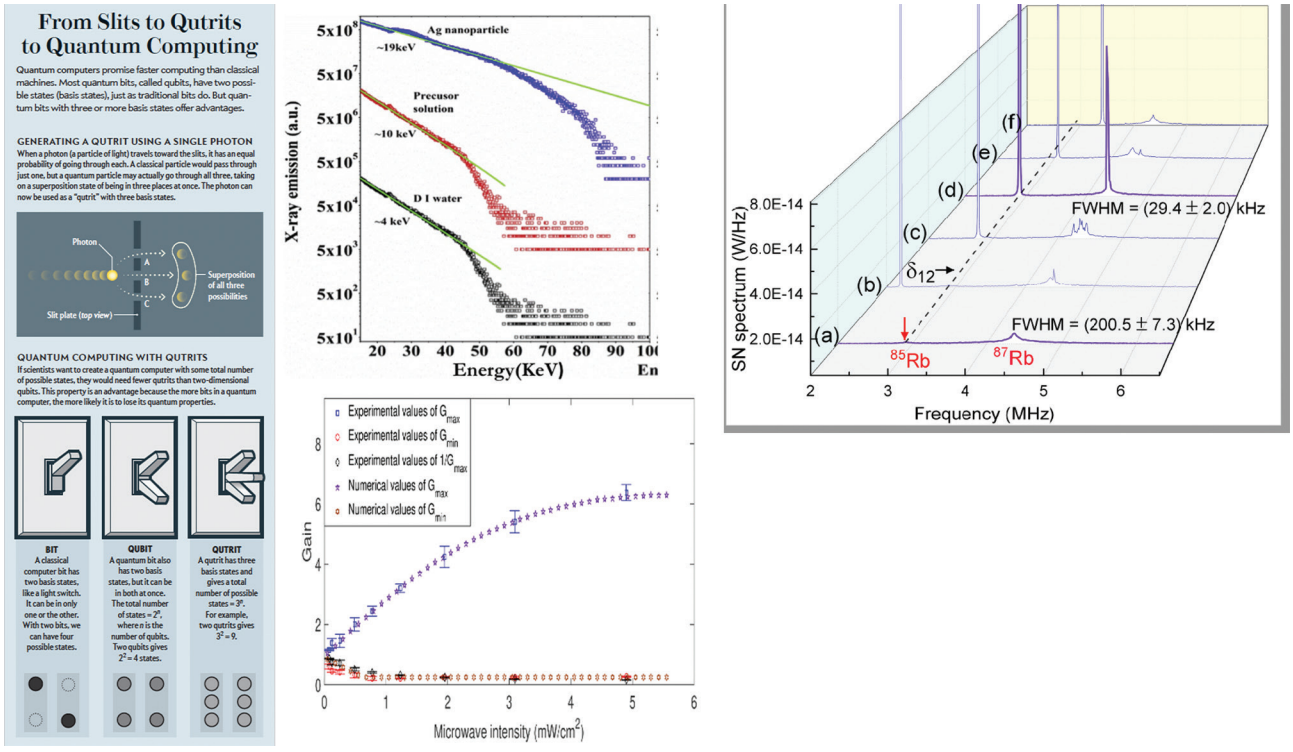
Quantum information, computing and Communication

The area of quantum communication and quantum information (QI) is a fascinating area spanning both fundamental and applied aspects of communication and information, which is qualitatively different from the existing technology of information exchange. The information transferring protocols of QI are based on the laws of quantum mechanics that give unprecedented information theoretic security of information transfer.

In the Quantum Information and Computing lab (QuIC) at RRI, Urbasi Sinha along with team members Rishab Chatterjee, Sourav Chatterjee, Kaushik Joarder, A. Nagalakshmi, A. Anuradha, Rakshita R.M. are working on several projects which include investigations of different quantum key distribution (QKD) protocols in free space, fibre as well as integrated photonic chips. QuIC lab is leading India's first satellite based QKD project in collaboration with the Indian Space Research Organization. Towards this project Urbasi Sinha and her team members established a QKD protocol called the B92 protocol in their lab with an average key rate of 46 Kbits/second and average QBER of 3.5% over a ~ 2 metre free space distance. They also came up with a much needed simulation toolkit, which is able to simulate end-to-end

QKD protocol taking into account practical experimental imperfections. This lab is one of the first labs in India to manufacture and apply single and entangled photons to varied physical problems. Acknowledging this the past year, Urbasi Sinha received an invitation to write a feature article reviewing the state of the art in single photon sources by the well-known broad spectrum optics magazine Optics and Photonics News (OPN) published by the Optical Society of America. The existence of a correction term to the Superposition Principle in slit based interference experiments was experimentally measured by them in 2018.

Originally Urbasi Sinha and her team had theoretically proposed the existence of this correction term. This year, Urbasi Sinha was invited to write an article on this entire body of work for the prestigious Scientific American. In the field of quantum information Urbasi Sinha and her collaborators C . Jebarathinam and D. Home have come up with a novel scheme whereby they have been able to find analytic relations between statistical correlation measures and known measures of entanglement. Also, Urbasi Sinha and Ashutosh Singh have come up with a entanglement preserving scheme for higher dimensional quantum systems.



(Left) *Illustration from Quantum Slits open New Doors, U.Sinha, Scientific American* (invited article), January 2020 issue [Illustration courtesy: Nick Bockelman] **(Top Middle)** Energy spectrum of bremsstrahlung X-ray emission measured in Ag and Au nanoparticle suspensions and their precursor solutions for a laser pulse intensity of 7.4 x 10^{14} W/cm^2. Total counts measured for the first 9000 laser pulses are shown [from P. Sankar et.al., Opt. Mat. **92**, 30 (2019)]. **(Top Right)** Direct detection of spin exchange collisions via spin correlation spectroscopy in Rubidium atoms. **(Bottom Right)** Maximum and minimum gain of the optical field plotted as a function of microwave intensity.

Soft Condensed Matter

Overview

Soft matter, as the name implies, encompasses materials that are easily deformed by thermal fluctuations and external forces. Some common examples of soft matter that we use in our day-to-day life include lotions, creams, milk and paint. The building blocks of these materials are macromolecules with typical size ranging anywhere from few nanometers to few micrometers and are held together by weak inter macromolecular forces and exhibit complex structures and phase behavior. The SCM group at RRI actively studies colloids, complex fluids, liquid crystals, nanocomposites, polyelectrolytes, self-assembled systems, polymers and biological materials. A fundamental understanding of the structure-property correlations, phase behavior of these systems, and response to external stimuli form a major part of the experimental research activities in the SCM group. Theoretical work carried out by the group broadly concerns developing phenomenological theories of stability, morphology and topological defects in soft matter.

Focus 2019-20

Liquid Crystals

As the name implies, liquid crystal (LC) is a state of matter that has properties intermediate between those of conventional liquids and solid crystals. An LC exhibits many of the physical attributes of a liquid, whereas its molecular units exhibit some form of order. Since their discovery, considerable work has gone into understanding their structure-property relationships, which hold the key for the myriad applications involving LCs. Researchers within the SCM group at RRI have done pioneering work in LCs and that tradition still continues today with research in various aspects of LCs being undertaken. The interesting physical properties resulting from a careful tuning of the molecular shape, concentration, constituents and phase, while expanding the LC knowledge base, serve to open potential avenues for technological applications. Research focus during 2019-20 was on design and synthesis of novel LC's and studying their physical properties, phase transitions and electro-optic properties as well as phenomenological theory of stability in curved surfaces.

Phase transition and electro-optics of liquid crystals

During the past year, experimental studies by Arun Roy and his PhD student Deepshika Malkar along with collaborator Veena Prasad in a type of Bent-Core Liquid Crystals have established two pseudopolar tilted smectic phases characterized by an in-plane axial-vector order parameter in addition to tilt order in the smectic layers whose birefringence in the mesophases was found to be strongly dependent on the applied electric field. A theoretical model was developed to account for this observation and it was found that the change in the birefringence of the sample arises from the field-induced reorientation of the tilt plane of the molecules in the layer above a threshold field.

Liquid crystals – phenomenological theory

Investigations of topological point defects on orientationally ordered spheres and on deformable fluid vesicles by Yashodhan Hatwalne, Arun Roy and RRI PhD student C Saichand along with collaborator Jayakumar Alageshan has shown that singular wall defects, topologically unstable "bald lines" in two dimensions are stabilized near the order-disorder transition on a sphere. They attribute this stability to free-energetic considerations, which override those of topological stability. This study was partly motivated by their potential applications in creating super-atoms with directional bonds through functionalization of the "bald-spots" created by topological point defects, thus paving the way for atomic chemistry at micron scales.

Mechanical Properties of Soft Materials

The transition of a liquid to a glass is a problem that has challenged condensed matter physicists for a long time. One of the objectives of Ranjini Bandyopadhyay's Rheology and Light Scattering laboratory is to use colloidal suspensions as model systems to experimentally unravel the mysteries of the glass transition. The group studies the mechanical properties of dense colloidal suspensions as they approach the jamming transition. These mechanical properties are correlated with structural information, obtained from microscopic or light scattering experiments, to better understand the onset of kinetic arrest (glassiness) in these suspensions. This group is also interested in making new colloidal materials by driving colloidal suspensions out of equilibrium. This is achieved by applying stresses or external fields. These experiments are expected to lead to the development of strong hydrogels with implications in the design of soft machines.

During the past year, Ranjini Bandyopadhyay and her PhD students Chandeshwar Mishra and Sanjay Behera synthesized thermoresponsive poly(N-isopropylacrylamide)(PNIPAM)

particles of different sizes and studied their properties using a variety of characterization techniques. Their study also included rheological measurements to understand the dynamics of these particles in jammed aqueous suspensions.

Soft materials show very interesting linear and non-linear mechanical behaviour. Many soft materials also change their mechanical properties depending on external cues in a controlled and reversible manner and can act as adaptable materials. One popular example is a dense suspension of corn starch in water ('oobleck') that can transform from a liquid-like to a solid-like state under sufficiently high applied force and comes back to the liquid-like state once the force is removed. Such adaptations can also be very subtle. For example, biopolymer networks formed by F-actin present inside the cells of our body can remember the history of applied stress. They can modify their mechanical response depending on the magnitude and direction of previously applied perturbations. One of the research directions of Sayantan Majumdar's lab is to understand and develop design strategies for materials that show force-induced adaptations.

Shear induced thickening and jamming transition in a well-controlled system of in house synthesized monodisperse spherical colloidal particles (polystyrene) in Polyethylene Glycol (PEG 400) was investigated during the past year by Sayantan Majumdar and his students Subhransu Dhar and Sebanti Chattopadhyay. Study of the signature of jamming under steady shear in these suspensions has shown that under high shear stress existing relations consistently overestimate the measured viscosity particularly for high particle volume fraction. A method to predict the onset of shear jamming was also proposed. In another work, using oscillatory shear rheology and in situ optical imaging, Sebanti Chattopadhyay and Sayantan Majumdar studied the yielding behaviour of a suspension formed by mixing hydrophilic amorphous granular particles with a hydrophobic solvent. The results from their study suggests that with increasing applied strain the system first reorganizes to form a more elastic solid-like state that dissipates minimum energy and then gets fluidized at higher strain values when the energy dissipation increases.

Biophysics

Nanoscale biophysics of biological systems

Gautam Soni's Nano-Biophysics lab's research interests are primarily guided by the role of force in biophysical structure formation and its synergy with functional dynamics. They try to understand mechanisms of force sensing as well as force response of cells and molecules. They study this in biological model systems of protein assembly, DNA-protein complexes as well as whole cell mechano-sensing. They use, as well as develop, novel bio-nano and micro scale tools to decipher biophysical principles governing role of forces in cellular as well as molecular assemblies. During the past year, Gautam Soni and his students M Sumanth Kumar and Koushik S have used their inhouse built quartz nanopores to quantify branched DNA on supercoiled plasmid and have studied its enzymatic linearization. Another research focus at the lab by Gautam Soni his students Saurabh Kaushik, Manohara M and collaborator Varadharajan Sundaramurthy was on measurement of alcohol dependent physiological changes in red blood cells using a novel high resolution electro-fluidic device developed in their lab. Their work presents first direct quantification of temporal and concentration-dependent changes in red blood cell volume upon ethanol exposure. Their device presents a universally applicable high-resolution and high-throughput platform to measure changes in cell physiology under native and diseased conditions.

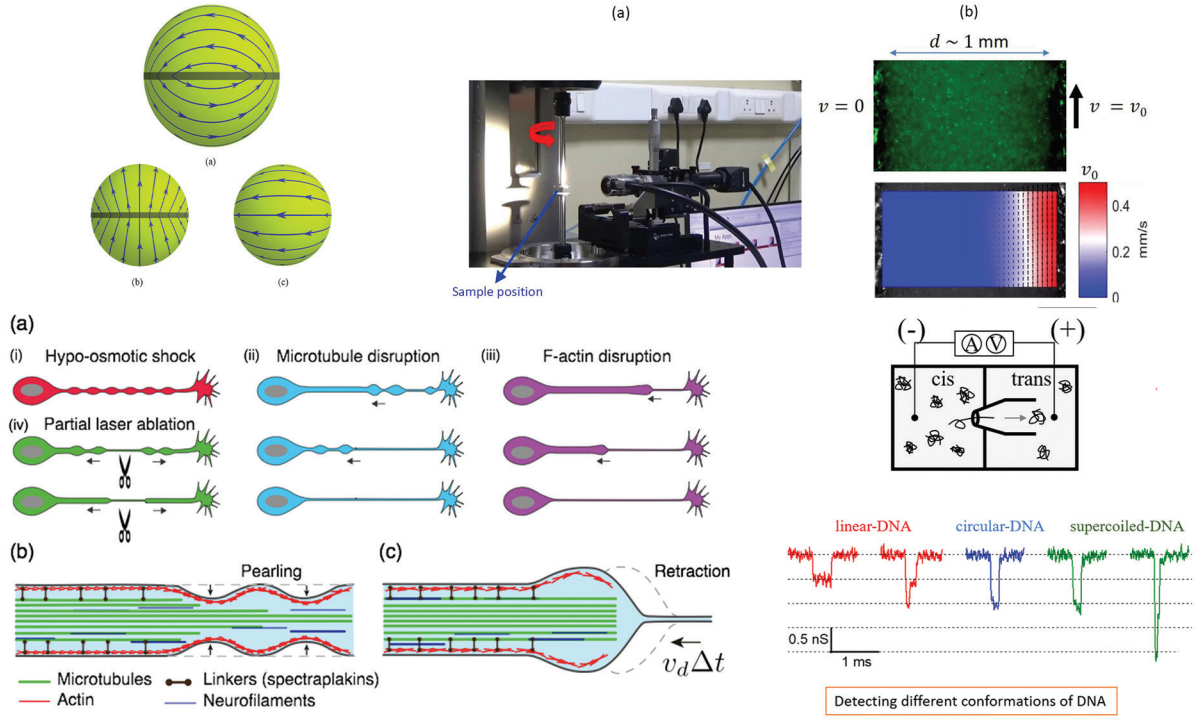
Biophysics of Axons

Research in Pramod Pullarkat's lab is towards studying the mechanical responses of axons. Axons are thin tubular extensions produced by neuronal cells in order to conduct electrical signals. In a human body they can be anything from a few tens of microns (in the brain) up to a meter long (in nerves extending into lower limps) with a diameter of only 1/1000th of a millimetre. They are also highly dynamic structures with an ability to grow, retract and rewire connections. At the same time, they need to have sufficient structural stability as they are subjected to large deformations during limb movements or as a result of injury. Not surprisingly, axons exhibit several remarkable mechanical properties. For example, they show unique viscoelastic responses to buffer fast mechanical stress, they can actively contract using molecular motors in order to minimise the length between connections (for fast signal transmission), and can exhibit tension induced lengthening at long times as during the growth of an organism. Recent experiments conducted in the laboratory by Pramod Pullarkat and his PhD student Sushil Dubey and others, along with collaborators Aurnab Ghose and Andrew Callan-Jones, using a home-developed, computer controlled force apparatus have shown that they buffer mechanical tension via special "shock-absorber" proteins called spectrins which can unfold and refold in response to mechanical stress giving rise to a strain-softening behaviour. Apart from exhibiting unique mechanical responses, axons can also undergo shape instabilities that originate from an interplay of membrane and bulk viscoelasticity. Axonal beading—formation of a series of swellings along the axon—and retraction are commonly observed shape transformations

that precede axonal atrophy in Alzheimer's, Parkinson, and other neurodegenerative conditions. Hence elucidating the mechanisms behind these shape transformations could lead to better prevention and treatment strategies. Recent research has shed light on the role of microtubules and membrane tension in axonal beading, retraction and atrophy. Studies of a particular type of spider silk using a Micro-Extension Rheometer - a device conceived, designed and built at RRI has revealed that silk fibers accommodate low values of applied strain by deforming relatively easily (softening) while they stiffen at higher values. A model developed for explaining similar behaviour in Axons was used to explain this response of spider silk. In general, the laboratory employs biological and genetic tools, novel measurement techniques and theoretical modelling to understand the various axonal responses to mechanical stress or neurodegenerative conditions.

Physics of Lipid Membranes and Polyelectrolytes

V A Raghunathan's group is involved in investigations on the structure of soft materials and their phase behaviour, using small-angle and wide-angle X-ray scattering techniques. Systems studied include lipid-sterol membranes, lipid-polyelectrolyte complexes and surfactant solutions. The phase behavior of these systems is also probed using optical and atomic force microscopy. In addition, the mechanical properties of lipid membranes are studied using optical microscopy and micropipette aspiration. During the past year, studies on electrostatic interaction by V A Raghunathan and his PhD student Anindya Chowdhury as a function of electrolyte ionic strength and its dependence on specific ion species has led to interesting observations. Current efforts are towards understanding this ion specificity. Studies of the aggregation behaviour of a mononucleotide and its salt in solution by V A Raghunathan, his student Sreeja Sasidharan and collaborator Himanshu Khandelia by using a variety of experimental techniques as well as computer simulations has led to a better understanding of their interaction with neutral lipid membranes. In spite of a large number of studies, presently there is no report of fluid-fluid coexistence in single component lipid membranes induced by an additive. V A Raghunathan and his PhD student Buti Suryabrahmam and RRI postdoctoral fellow Ayush Agrawal have recently found that 1-decanol induces fluid-fluid coexistence in dimyris- toylphosphatidylcholine (DMPC) membranes.



(Top Left) Equatorial wall: (a) Side ($\theta = \pi/2$, $\varphi = \pi/2$ at the centre) view of the index 2, equatorial wall. The directed lines are the streamlines of the vector field. The shaded region represents the disordered core, within which vector order is completely destroyed, and cannot be assigned a direction. The full field, including that shown within the core region, corresponds to a wall with zero core-size. Rounding off the slope singularity of the field at the equator, the wall defect of zero core-size transforms into the antipodal configuration of a pair of index 1 point disclinations. (b) Front view ($\theta = \pi/2$, $\varphi = 0$ at the centre). (c) Top view, showing that the polar regions are free of point disclinations. **(Top Right)** (a) Experimental set-up for rheology and in-situ velocity profile measurements. (b) Typical PIV vectors indicating shear banding in the system under steady-shear (sample: corn starch particles in paraffin oil with $\phi = 20\%$). **(Bottom left)** Schematic diagrams showing the variety of shape instabilities exhibited by axons under different perturbations.**(Bottom Right)** Detecting different conformations of DNA.

Theoretical Physics

Overview

Theoretical physics is an endeavour that attempts to make sense of the inner workings of nature, using the language of mathematics. The goal is to model and predict the behaviour of all physical systems from the very small (sub-atomic and smaller) to the very large (galaxies and beyond) that constitute this beautiful and complex universe that we live in. The Theoretical Physics group at RRI is actively pursuing research in the following areas: Foundations of Quantum Mechanics, General Relativity, Quantum Gravity, Statistical Physics, Condensed Matter and Atomic, Molecular & Optical (AMO) Physics. RRI theorists have fruitful ongoing collaborations in these research areas with both national and international scientists. The TP group has also forged a robust collaboration with experimental groups within RRI. The connection with Light and Matter Physics group is specifically in the areas of precision measurements using atomic systems, foundational questions in quantum mechanics and quantum information. The overlap with the Soft condensed matter group is in areas such as biophysics, polymer physics and modelling stochastic search process.

Focus 2019-20

Statistical Physics

Statistical physics comprises a set of mathematical techniques that can be applied to a physical system to estimate its properties. Simply put, statistical techniques derive high-level (macroscopic) descriptions starting from low level (microscopic) ones after averaging out a lot of details. Finding the correct method of averaging out the details is key to the statistical method for investigation of physical systems. As an example, consider a box filled with gas. A correct statistical average of the momentum and position of individual atoms is mandatory for accurate descriptions of macroscopic quantities such as temperature and pressure. Researchers at RRI routinely employ statistical methods to understand physical systems.

Active particles are self-propelled agents which consume energy from environment and convert it into directed motion. Apart from various interesting collective phenomena, active particles also show a lot of novel behaviour even at the level of individual particles. One of the main research interests is to study and characterize the properties of single active particles, using simple, analytically tractable models.

During 2019-20, Urna Basu, and collaborators Satya N. Majumdar, Alberto Rosso and Gregory Schehr studied the late time dynamics of a single active Brownian particle in two dimensions and have shown that at late times, while the position probability distribution approaches a Gaussian form near its peak describing the typical diffusive fluctuations, it has non-Gaussian tails describing atypical rare fluctuations. During the past year, Urna Basu, Sanjib Sabhapandit and collaborators Satya N Majumdar, Alberto Rosso and Grégory Schehr have for the first time solved exactly the stationary position distribution of a one-dimensional run-and-tumble (RTP) particle with three discrete internal states when it is subjected to an external harmonic potential. In another work, calculations of marginal position distributions for certain orientations of a set of RTP in two dimensions by Ion Santra, Urna Basu and Sanjib Sabhapandit has revealed that in both cases the RTP shows a crossover from a ballistic to diffusive regime. The orientational probability distribution of an active Brownian particle(ABP) at various time regimes was analytically studied by Supurna Sinha, which can help in understanding behaviour of biological systems like bacteria or soft matter systems like driven granular matter, swimming microbes, schools of fish and swarms of birds. Studies of a gas of point particles with hard-core repulsion in one dimension where the particles move freely in-between elastic collisions by Sanjib Sabhapandit and collaborators Aritra Kundu and Abhishek Dhar has led to the computation of exact long-time spatio-temporal correlation functions of arbitrary powers of velocities for these particles. Recently, Urna Basu and Onkar Sadekar (visiting student at RRI) have studied the dynamics of symmetric exclusion process (SEP) in the presence of stochastic resetting to specific configurations and have shown that this dichotomous resetting leads to a range of rich behaviour, both dynamical and in the stationary state. In work done during the past year, Sanjib Sabhapandit and collaborator Deepak Gupta investigated the entropy production of a particle in a (i) harmonically coupled Brownian particle system and (ii) harmonically coupled system of particles in harmonic confinement in a heat reservoir at a constant temperature maintained in the non-equilibrium steady state using stochastic driving. They found that in the weak coupling limit, the entropy produced by the partial system of the coupled system in a harmonic trap satisfies the steady state fluctuation theorem

During the past year, Supurna Sinha, PhD student Ion Santra and collaborators Avijit Das, Abhishek Dhar and Urbashi Satpathi have investigated in detail

the well-known Rubin bath model, which consists of a one-dimensional harmonic chain with the boundary bath particle coupled to the Brownian particle. They have shown how in the limit of infinite bath bandwidth, they get the Drude model and a second limit of infinite system-bath coupling gives the Ohmic model. A detailed analysis of relevant correlation functions were undertaken and related to recent work using linear response theory to understand quantum Brownian motion.

Classical and Quantum gravity

The construction of fully quantum mechanical description of the gravitational interaction remains the outstanding open problem in fundamental theoretical physics. Quantum gravitational effects are expected to be dominant in extreme situations such as at the Big Bang and deep inside Black Holes. Einstein's General Relativity identifies gravitation as arising with the geometry of space and time. Hence, a theory of Quantum Gravity is expected to revolutionise our very notions of spacetime and would herald a paradigm shift exceeding that following the discovery of Quantum Mechanics. Two different approaches to Quantum Gravity are pursued at RRI. One is a canonical continuum approach, Loop Quantum Gravity and the other is a discrete path sum approach, Causal Set Theory

Loop Quantum Gravity

Loop Quantum Gravity (LQG) generalizes standard quantization techniques to a context in which there is no fixed spacetime geometry. The application of LQG techniques to General Relativity seems to hint at a discrete fine structure underlying the continuum classical theory. A network of interconnected loops builds the space that we see around us; the smooth nature of space that we encounter is because we see it from a distance - something akin to matter looking smooth from afar even though it is made of atoms. For example, the area of any spatial region is proportional to the number of threads entering the enclosed surface. LQG attempts to generalize the familiar techniques of quantum mechanics and quantum field theory and apply them to the context of gravitation. This generalization is technically and conceptually very intricate because, unlike the case of quantum field theory where the quantum fields evolve on a fixed spacetime, here it is the very geometry of spacetime that is dynamical. Hence one needs a generalization that does not rely on notions of a background fixed spacetime. While one has a fine understanding of how to describe quantum spatial geometry in LQG (`LQG kinematics'), a key open problem is how to describe quantum spacetime geometry (`LQG dynamics').

Over the last decade, Madhavan Varadarajan has focussed on an extremely non-trivial system which is obtained as a novel weak coupling limit of Euclidean General Relativity and which exhibits an algebra which is isomorphic to that of Euclidean gravity. In the recent past, he has developed quantum dynamics that leads to vigorous propagations in quantum perturbations in the above system. Over the last year he has made significant progress through the introduction of several new ideas and techniques and expects a complete solution in the near future.

Causal Set Theory

Causal Set Theory (CST) is a manifestly covariant approach to quantum gravity, which assumes that spacetime is fundamentally discrete. CST is motivated by deep theorems in Lorentzian geometry, and gives primacy to the causal ordering of spacetime events. In CST the causal structure (which is a partially ordered set) is quantised. It posits that the continuum is an approximation to an ensemble of underlying locally finite partially ordered sets or causal sets.

During 2019-20, Sumati Surya and collaborator William Cunningham simulated dimensionally restricted non-perturbative quantum gravity dynamics in 2 and 3 spacetime dimensions with non-trivial global spatial topology. In both cases, they found a phase transition which separates the deep quantum regime from the continuum regime. An important feature of quantum field theory on a generic curved spacetime is the lack of a preferred vacuum which reinforced the algebraic approaches to quantum field theory in curved spacetime, which are defined without reference to a vacuum. In the last decade or so, a new prescription has emerged for an observer-independent vacuum, the so-called Sorkin-Johnston or SJ vacuum. During 2019-20, the central SJ eigenvalue problem was solved in 2d Minkowski spacetime by Sumati Surya and her PhD student Abhishek Mathur in the small mass limit. An open question in horizon physics, which includes blackhole physics, is how much of the horizon entropy can be attributed to Entanglement Entropy (EE). Using the Sorkin-Johnston vacuum, Sumati Surya and her PhD student Nomaan X along with collaborator Yasaman Yazdi have calculated the spacetime entanglement entropy (SSEE) for de Sitter horizons in 2 and 4 dimensions using a causal set discretisation for a conformally coupled free scalar field. They found that not only is an area law satisfied with an appropriate truncation of the Sorkin-Johnston spectrum, but also that the SSEE satisfies complimentarity.

Classical and Quantum Foundations, Information and Optics

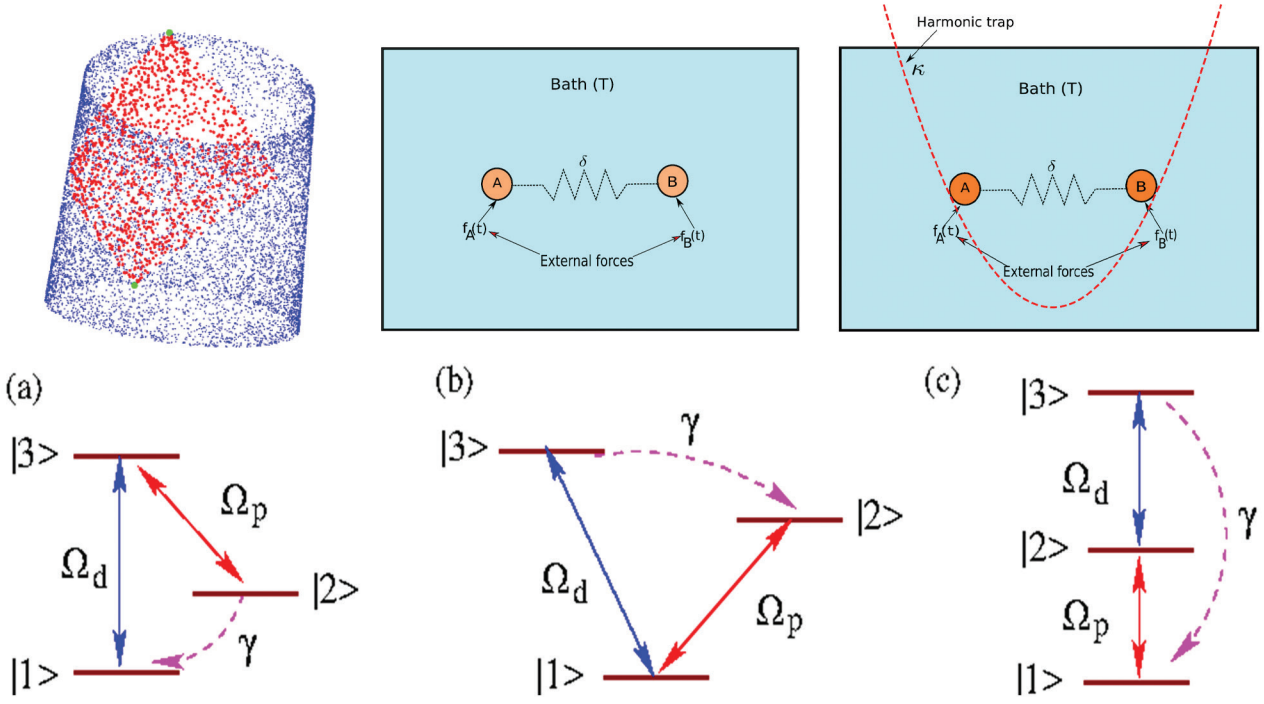
Research at the Institute under the Quantum Theory theme is towards investigating foundational questions including quantum information, quantum interpretation, quantum optics and the geometry behind quantum theory.

The quantum no-cloning theorem states that an arbitrary quantum state cannot be cloned perfectly. During the past year, Anirudh Reddy, Supurna Sinha and Joseph Samuel investigated the issue of cloning of states in the classical domain and explicitly showed how perfect classical cloning can be implemented using Hamiltonians. They also investigated how statistical mechanical noise leads to imperfection while cloning classical states and have discussed possible experimental demonstrations of their ideas.

Condensed Matter and Atomic, Molecular & Optical (AMO) Physics

Research at the Institute in Condensed Matter and AMO physics is towards understanding nonequilibrium quantum dynamics in solid-state and AMO systems applying physical laws, particularly the laws of quantum mechanics, electromagnetism, and statistical mechanics. While the topics of interest in condensed matter are disordered systems, superconductors, and topological materials, the research in AMO is mainly in waveguide quantum electrodynamics and precision measurements using atomic vapors and ultracold atoms.

In one work, Vivek Vyas, Dibyendu Roy and Joseph Samuel have found a geometric phase - the Pancharatnam-Zak phase - gained by an electron in a one-dimensional periodic lattice due to weak electric perturbation. As



(top left) The spacetime entanglement entropy was calculated for the causal diamond in deSitter spacetime, and shown to be proportional to the de Sitter horizon area. **(top right) Left panel:** Two Brownian particles (A and B) are coupled with a spring of coupling parameter $\delta = 2km/\gamma^2$ (dimensionless). The whole system is in contact with a heat bath of constant temperature T. The external stochastic Gaussian forces $f_A(t)$ and $f_B(t)$ are acting on the particles A and B, respectively. **Right panel:** The whole system in confined in a harmonic trap of strength $K = mk_0/\gamma^2$ (dimensionless). (bottom) Cartoon of 3LEs with levels |1>, |2>, |3>. Three different arrangements for the coupling of probe (red arrow) and drive (blue arrow) beams with the allowed transitions they make (a) Λ, (b) V , and (c) ladder-type configuration of the 3LE. Here, Ωp and Ωd are respectively the Rabi frequency of the probe and drive beam, and γ denotes the strength of non-radiative decay.

opposed to the well-known Zak phase, the Pancharatnam-Zak phase is a gauge invariant observable phase, and correctly characterizes the energy bands of the lattice. The measurement of the single-particle Pancharatnam-Zak phase in individual topological phases, as well as the statistical contribution in its many-particle generalization, should be accessible in various controlled quantum experiments. Duirng the past year, Dibyendu Roy and his PhD student Atul Vinu have explored amplification and cross-Kerr nonlinearity by a three-level emitter (3LE) embedded in a waveguide and driven by two light beams. In particular, they have calculated the regime of the probe and drive powers when the 3LE acts most efficiently as a coherent amplifier, and have derived the second-order coherence of amplified probe photons. They have applied the Kramers-Kronig relations to correlate the amplitude and phase response of the probe beam, which are used in finding the coherent amplification and the cross-Kerr phase shift in these systems.

Closing remarks

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

RRI is well aware of its indebtedness to society, the DST and the Government of India for their excellent support. The basic science research conducted at RRI continually advances knowledge base resulting in improved understanding of the fundamental laws and behavior of nature. This is the seed that eventuates into innovations and provides the foundations and solution banks for organizations that directly target societal issues and engage in translational research. Nevertheless, the basic science research at RRI does also result in outcomes that directly impact on the quality of life; examples are the development of a brain computer interface involving a visually activated control system for use in wheel chairs, elevators etc., and successful demonstration of real time imaging through fog in the field involving a novel low-cost method that utilizes an inexpensive incoherent light source, a low-cost scientific camera, and a software developed for this purpose, with obvious applications in defense, search and rescue and medical imaging to name a few. Other examples are optical limiters for laser safety applications, a nanopore platform for single DNA molecule detection, a milk purity testing device involving an electrochemical impedence measuring device to detect synthetic milk, with potential to save multitudes from adverse health effects and translates into physical well-being of people. RRI has also leveraged its long standing expertize in liquid crystals to develop organic photovoltaics and optoelectronics platforms.

The Institute has a number of schemes that engenders creativity, higher learning and experimental skills in the next generation. In the last year, the scientific staff at RRI have mentored and educated around 200 students and young researchers, and provided opportunities for development of their potential towards being the scientists of tomorrow, by engaging with them in the Post-doctoral, PhD, Research Assistant, and Visiting Student Programmes.

RRI exercises its social scientific responsibility: by hosting events wherein the society in general and young people in particular are invited to the Institute and its field station, and by dissemination of knowledge via active participation in Governmental outreach events, popular lectures, visits and workshops given by RRI staff in various external institutions, schools, colleges and universities. RRI has an ever-increasing digital footprint with regular posts in facebook, twitter and blogs of recent scientific results written in a language that is easily understandable to the general public. The official RRI YouTube channel has now grown to include videos of lectures, conferences, seminars and workshops organized at the Institute.

Research: Knowledge Creation

Astronomy and Astrophysics

Astronomy and Astrophysics

Overview

From the beginning humankind has looked up at the sky with a sense of curiosity and wonderment. It is no wonder that astronomy is one of the oldest of natural sciences. The field of Astronomy and Astrophysics pertains to a detailed study of the physical, chemical and dynamic properties of celestial objects and phenomena. The research conducted in the AA group at RRI can be broadly classified into four areas:

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

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

(c) Experimental Astronomy involves the design, construction and operation of telescopes for very specific purposes to address key unsolved problems, and are strategically located around the world and in space.

(d) Algorithms & Signal processing where a variety of methods and modelling are employed to amplify and or isolate the required astronomy signal from other foregrounds, backgrounds and unwanted interference and confusion.

Focus 2019-20

Theoretical Astrophysics and Cosmology

The universe that we inhabit is vast beyond comprehension, complex, constantly expanding and is populated by myriad astronomical entities. The universe is populated by stars, galaxies, galaxy clusters, high energy objects like blazars and more. The space between stars, galaxies, galaxy clusters and the roughly spherical region that extends out from a galaxy is permeated by diffuse gas and dust. These are known as interstellar medium, intergalactic medium, intracluster medium and circumgalactic medium respectively. The Universe is a very vibrant place with constant interactions and various dynamic processes that shape their evolution and in turn the evolution of the universe as a whole. By studying these cosmic entities, their interactions and processes Astrophysicists, and on a much larger scale, Cosmologists try to understand the evolution of the universe and its workings within the framework of the known laws of physics and chemistry. Analytical modelling and/or numerical simulations shed light on these processes and add to the knowledge base of our understanding of the Universe. A detailed description of the research focus in Theoretical Astrophysics and Cosmology undertaken at the Institute during 2019-20 follows.

Interstellar Medium

Optical and IR signatures of high redshift host galaxies of supermassive black holes

With collaborators Eugene Vasiliev and Yuri Shchekinov, Biman Nath has been studying the optical and IR lines whose properties could be used as a diagnostic for measuring the supermassive black hole mass, the gas mass in the galaxy and the stellar mass. This will be useful for upcoming James Webb Space Telescope (JWST) mission. Using photoionization codes to shine high energy emission from the black hole and stellar radiation on the interstellar medium, which may or may not contain dust and may have metallicity different from the present-day, they have selected a few resulting nebular lines, whose ratio may be useful for estimating the three important masses mentioned above. This work has been submitted for publication in Monthly Notices of the Royal Astronomical Society.
[Eugene O. Vasiliev (Southern Federal University, Russia), Yuri A. Shchekinov (Lebedev Physical Institute of Russian Academy of Sciences, Russia) and Biman Nath]

Galactic Outflows

Superbubbles in the Milky Way

With a Masters student Pushpita Das, Biman Nath has done Monote-Carlo simulation of superbubbles in a disc galaxy and compared the size distribution with that observed in THINGS survey. Previous theoretical work on size -distribution used adiabatic evolution of superbubbles (Oey & Clarke 1997). In this work they have included the effects of cooling and non-thermal pressure in ISM, using hydrodynamical simulations of bubbles, and compared

them with observations. This work was published in the Monthly Notices of the Royal Astronomical Society. (Volume 493, Issue 1, March 2020, Pages 1034–1043).
[Biman Nath, Pushpita Das (IISER, Kolkata), M S Oey (University of Michigan, USA)]

Cosmic rays from Superbubbles—isotope ratio

During the past year, Biman Nath, Siddhartha Gupta and collaborators Prateek Sharma and David Eichler have been working on the implications of superbubbles being sites of cosmic ray acceleration, with regard to Neon (22 to 20) isotope ratio. With detailed realistic modeling of the wind termination shock, they have shown that this can be explained if roughly a quarter or more Galactic cosmic rays is accelerated in star cluster (the rest coming from SN remnants). This work is published in Monthly Notices of the Royal Astronomical Society. (Volume 493, Issue 3, April 2020, Pages 3159–3177)
[Biman Nath, Siddhartha Gupta, Prateek Sharma (Indian Institute of Science, Bengaluru) and David Eichler (Ben-Gurion University of the Negev, Israel)]

Role of cosmic rays in galactic outflows

With his PhD students Ranita Jana and Siddhartha Gupta, Biman Nath studied the role of cosmic rays in galactic outflows, with detailed hydrodynamical 2-fluid simulations, and corrected the mistaken lore that cosmic rays dynamically affect outflows. They were able to demonstrate this using their expertise on cosmic rays in the dynamics of star clusters and in galactic outflows. This work has been submitted to MNRAS and is under referee review.
[Ranita Jana, Siddhartha Gupta and Biman Nath]

Galactic Structure and Stellar Dynamics

Spiral structure of disc galaxies

The spiral patterns of disc galaxies like the Milky Way are some of the most beautiful structures formed by stars and gas in the universe. They are density enhancements, driving disc evolution through new star formation and angular momentum transport. The density-wave theory of the 1960s failed to produce long-lived spiral patterns because the wave is absorbed at Lindblad resonances. Further progress came through careful numerical experiments, which suggested that spiral structure could arise from transient modes that create conditions conducive for their regeneration. S Sridhar has developed a theoretical framework in which mode renewal can be understood from first principles. Briefly, a transient spiral mode leaves behind "resonant scars" in phase space. He used the nonlinear theory of adiabatic capture into resonance to calculate the finite changes in the distribution function of stars in the scars, which are concentrated around resonances. He then showed that mode dissipation is suppressed within scars, so they act as filters of the spectrum of noise-generated modes, thereby promoting the renewal of a few select modes. Thus the main obstacle to the problems of spiral structure, encountered in the 1960s, is removed. There is a further bonus to this way of viewing the problem: "relic scars" sustained by a galaxy disc, due to past tidal interaction with a passing companion, may still be active enablers of two-armed "grand design" spiral patterns. This work has been published in The Astrophysical Journal.

Having introduced the concept of "scarred" galactic discs, Sridhar's current efforts have been towards exploring the following questions. It is well known (since the 1960s) that "smooth" discs do not sustain linear spiral modes because these get absorbed at Lindblad resonances. But this need not be the case in a scarred disc because the distribution function of stars in region around the Lindblad resonances is modified. Can scarred galactic discs sustain spiral density waves? In particular, could these arise as linear instabilities?
[S Sridhar]

Stellar dynamics in galactic nuclei

During the past year, S Sridhar has continued to work on the dynamics of dense star clusters orbiting supermassive black holes in galactic nuclei, particularly the angular momentum transport and dynamical instabilities which create asymmetric structures, responsible for enhanced mass accretion to the center.
[S Sridhar]

High Energy Astrophysics

The High Energy Astrophysics group at RRI is involved in modelling of propagation of Galactic and extragalactic cosmic rays with Monte Carlo simulations. They do multi-wavelength modelling of Galactic and extragalactic gamma ray sources to reveal the underlying physics of high energy particle production within cosmic accelerators.

Ultrahigh-energy cosmic ray interactions as the origin of very high energy gamma-rays from BL Lacertae objects

Nayantara Gupta and her PhD student Saikat Das along with collaborator Soebur Razzaque have explained the observed multiwavelength photon spectrum of a number of BL Lacertae (BL Lacs) objects detected at very high

energy (VHE, E>~30 GeV), using a lepto-hadronic emission model. They employed the one-zone leptonic emission to fit the synchrotron peak and calculated the SSC spectrum, such that it extends up to the highest energy possible for the jet parameters considered. The data points beyond this energy, and also in the entire VHE range are well explained using a hadronic emission model. The ultrahigh-energy cosmic rays (UHECRs, E>~0.1 EeV) escaping from the source interact with the extragalactic background light (EBL) during propagation over cosmological distances to initiate electromagnetic cascade down to ~1 GeV energies. The resulting photon spectrum peaks at ~1 TeV energies. They considered a random turbulent extragalactic magnetic field (EGMF) with a Kolmogorov power spectrum to find the survival rate of UHECRs within 0.1 degrees of the direction of propagation in which the observer is situated. Restricting the RMS value of EGMF, B_{rms} ~10^{-5} nG, for a significant contribution to the photon spectral energy distribution (SED) from UHECR interactions they found that UHECR interactions, on the EBL and secondary cascade emission can fit gamma-ray data from the considered BL Lacs at the highest energies. This study has shown that the required luminosity in UHECRs and corresponding jet power are below the Eddington luminosities of the super-massive black holes in these BL Lacs.
[Saikat Das, Nayantara Gupta and Soebur Razzaque (University of Johannesburg, South Africa)]

Positron Excess from Cosmic Ray Interactions in Galactic Molecular Clouds

The recent data on cosmic ray (CR) positron flux measured near the Earth by the Alpha Magnetic Spectrometer (AMS-02) experiment extends to TeV energy. The positron flux measured in GeV^2 m^{-2} sec^{-1} sr^{-1} rises with energy and shows a peak near a few hundred GeV. This rising positron flux cannot be explained by interactions of cosmic rays with interstellar hydrogen gas. Due to the progress in multi-wavelength astronomy, many new Galactic Molecular Clouds (GMCs) have been discovered in our Galaxy recently. Agnibha De Sarkar, Sayan Biswas and Nayantara Gupta have used the updated list of GMCs, which are distributed in the Galactic plane, to find the secondary positrons produced in them in interactions of cosmic rays with molecular hydrogen. Moreover, by analysing the Fermi LAT data, new GMCs have been discovered away from the Galactic plane. Some of these GMCs closest to the Earth where cosmic ray interactions are producing secondaries were also included in the study. It has been speculated earlier that CRs may be reaccelerated in some GMCs. Assuming reacceleration is happening in a few GMCs, which are yet undetected and after including a small hardened component of secondary positrons, produced from interaction of reaccelerated CRs in those undetected GMCs, this study has shown that the observed positron spectrum can be well explained in the energy range of 1 to 1000 GeV.
[Agnibha De Sarkar, Sayan Biswas and Nayantara Gupta]

Gamma-Ray Flares in Long Term Light Curve of 3C 454.3

3C 454.3 is frequently observed in flaring state. Analysis of the long term light curve of this source with 9 year (August 2008 - July 2017) data from Fermi LAT detector has enabled Nayantara Gupta and her PhD students Avik Kumar Das and Raj Prince identify five flares and one quiescent state. The flares were found to have sub-structures with many peaks during flaring phase. Estimates of the rise and decay time of the flares were compared with flares of other similar sources. The modeling of gamma ray spectral energy distributions has shown that in most cases Log parabola function gives the best fit to the data. Time dependent leptonic modeling of two of the flares, for which simultaneous multi-wavelength data are available has revealed that these two long lasting flares Flare-2A and Flare-2D continued for 95 days and 133 days respectively. The average values of Doppler factor, injected luminosity in electrons, size of the emission region and the magnetic field in the emission region was used in modeling these flares. The emission region was assumed to be in the broad line region in their single zone model which includes the energy losses (synchrotron, synchrotron self-Compton, external Compton) and escape of electrons from the emission region while doing the modelling. Although, the total jet powers required to model these flares with leptonic model are higher compared to other sources, they were found to be always lower than the Eddington's luminosity of 3C 454.3. Through this study it was shown that the time variation of the Doppler factor or the injected luminosity in electrons over short time scales can explain the light curves of select flaring peaks.
[Avik Kumar Das, Raj Prince and Nayantara Gupta]

Modeling the spectrum and composition of ultrahigh-energy cosmic rays with two populations of extragalactic sources

Nayantara Gupta, her PhD student Saikat Das and collaborator Seobur Razzaque have fitted the ultrahigh-energy cosmic-ray (UHECR, above energy 0.1 EeV) spectrum and composition data from the Pierre Auger Observatory at energies above 5 EeV, i.e., beyond the ankle using two populations of astrophysical sources. One population, accelerating dominantly protons (1H), extends up to the highest observed energies with maximum energy close to the GZK cutoff and injection spectral index near the Fermi acceleration model; while another population accelerates light-to-heavy nuclei (4He, 14N, 28Si, 56Fe) with a relatively low rigidity cutoff and hard injection spectrum. It was found that a single extragalactic

homogeneous source population with a mixed composition (1H, 4He, 14N, 28Si, 56Fe) at injection leads to zero 1H abundance fraction, while fitting the spectrum at energies more than 5 EeV. With their choice of exponential cutoff power-law injection spectrum and sybill2.3c hadronic interaction model, they investigated the effects on composition predictions and other UHECR source parameters, as one goes from a single-population to two-population model. For the latter, a non-zero 1H abundance was found to be inevitable at the highest energies, and a significant improvement in the combined was noted on addition of a pure-proton spectrum. The proton injection index was varied to find the best-fit parameter values of the two-population model, and the maximum allowed proton fraction was constrained at the highest- energy bin within 3.5 sigma statistical significance. The expected cosmogenic neutrino flux in such a hybrid source population scenario was computed. This study also considered the possibilities to detect these neutrinos by upcoming detectors to shed light on the sources of UHECRs.
[Saikat Das, Soebur Razzaque(University of Johannesburg, South Africa) and Nayantara Gupta]

Possible γ-ray sources of northern hemisphere muon track events

The first ever identification of a cosmic ray accelerator as the consequence of spatial and temporal correlation of IceCube event 170922A with flaring of a blazar TXS 0506+056 motivated Nayantara Gupta and collaborators to look for other flaring blazars in Fermi-LAT 3FGL catalog, which could be correlated with IceCube high energy track events. The Fermi-LAT light curves of blazars correlated with neutrino track events were studied. Among the eight sources identified within 2^0 angular uncertainty of the IceCube track events selected in this study, only one source 3FGL J2255+2409 was found to be in flaring state during the neutrino detection. The authors carried out a time dependent modelling of the multi-wavelength data from this blazar, and the neutrino event including leptonic energy losses and proton-proton interactions in its jet to determine whether it could be the origin of the neutrino event. Their lepto-hadronic model estimates a jet luminosity of L_j=3.6 $\times 10^{47}$ ergs/sec during the neutrino phase of 3FGL/4FGL J2255+24011.
[Nayantara Gupta and collaborators R Moharana et al.]

Modelling the Broadband Emission of Two Flares of 3C 273 in Early 2010

During the past year, the temporal and spectral variability of two flares of 3C 273 in early 2010 were studied and modelled with a two zone emission model by Nayantara Gupta and collaborators Sonal R. Patel and Debanjan Bose.
[Sonal R. Patel, Debanjan Bose, Nayantara Gupta]

Cosmology

Impact of primordial black holes on reionization era: ^{3}He line

The cosmological implications of the formation of the first stellar size black holes (BHs) in the universe was studied by Shiv Sethi and collaborators Eugene Vasiliev and Yuri Schehinov. They considered emissions from the influence zones around accreting BHs during $8.5 < z < 25$. Considering the hyperfine line of ^{3}He II as the main observable they have shown that the region around the BH could produce brightness temperatures 10 μK across an evolving structure of 100 kpc with hot, ionized gas closer to the BH and much cooler gas in outer regions. This work has shown that current and upcoming radio interferometers such as the Square Kilometre Array (SKA) SKA1-MED might be able to detect these regions.
[Eugene Vasilliev (Rostov university, Russia), Yuri Schechinov (Lebedev Institute, Russia) and Shiv Sethi]

Charged cold dark matter

The cosmological implications of stable charged particles as cold dark matter in the universe was considered by Shiv Sethi and A P Gautham, a visiting student at RRI. Three models were studied: (a) milli-charged dark matter, (b) an atom formed between two heavy charged particles, (c) an atom formed between helium nucleus and a heavy charged particle. They derived the relevant scattering cross-sections of these particles with other charged particles and modelled their interaction with the rest of the matter using fluid approximation and studied both the coupled and uncoupled regimes. Cosmological observables were then computed both analytically and numerically and the results were compared with Planck CMB data.
[A. P. Guatham (a visiting student from IIT, Madras) and Shiv Sethi]

Post reionization era and the large scale structure of the universe

Studying the post-reionization era constitutes an important area of research in modern-day cosmology. In this era, bulk of the neutral hydrogen (HI) resides in those dense pockets within the galaxies that have HI column number densities $N_{HI} \geq 2 \times 10^{21}$ atoms/cm^2. These regions are identified as the damped Lyman Alpha (DLAs) in quasar observations. Different from the galaxy surveys, observations of the HI 21-cm signal do not resolve the individual HI sources, and the collective emission from these sources appear as background radiation in HI 21-cm observations. Fluctuations in this background radiation carries the imprint of the underlying source clustering at that epoch. These fluctuations are ordinarily quantified

using a quantity called the HI power spectrum, which gives the correlations of the HI fluctuations measured in Fourier space. Measuring the HI power spectrum can help us to address several issues related to the HI distribution and the formation of the large scale structure in the universe.

In the past few years, Anjan Sarkar's research has been primarily centered on making predictions for measurements of the HI 21-cm signal using the upcoming radio telescopes like the Ooty Wide Field Array (OWFA) and the Square Kilometer Array (SKA). Along with collaborators he has carried out analyses to forecast the possibilities of measuring the HI power spectrum and the cross power spectrum of the HI 21-cm signal and the Lyman-α forest using OWFA in the Cold Dark Matter (CDM) scenario. Recently, predictions were made for the measurements of the cross power spectrum in a Warm Dark Matter (WDM) scenario using two different radio telescopes, OWFA and SKA. Besides these, in an earlier work, an analytical method to simulate HI signal visibilities was proposed.

Summary of the works carried out under this broad research theme in 2019-20 is given below.

Constraining the Warm Dark Matter (WDM) power spectrum and its mass using the cross-correlation of the HI 21-cm signal and the Lyman- forest

Anjan Sarkar and collaborators Ashis Pal and Tapomoy Sarkar have used the observations of the cross-correlation of the HI 21-cm signal and the Lyman- forest with an linear radio-interferometric array, namely the Ooty Wide Field Array (OWFA) and an futuristic large radio telescope like SKA1-mid, and an large scale spectroscopic survey like BOSS of SDSS-IV, to place constraints on the cross WDM power spectrum and on the WDM mass. Considering observations of 200 hours each in 100 different, independent fields-of-view with OWFA and the WDM mass, $m_{WDM} = 0.25$ kev, they have found that it is possible to measure the cross WDM power spectrum with SNR ≥ 5 in multiple k-bins at $k \leq 0.45$ Mpc^{-1} . However, OWFA will be insensitive towards measuring the suppression of the WDM power spectrum, and thereby towards constraining the WDM mass. Considering SKA1-mid, they found that for a fiducial $m_{WDM} = 0.25$ keV, the suppression in the cross power spectrum can be measured at $\sim 10\ \sigma$ around $k \sim 0.2$ Mpc^{-1} for a total observing time of 20000 hours distributed uniformly over 50 independent pointings. This work is published in the Journal of Cosmology and Astroparticle Physics (JCAP).
[Anjan Kumar Sarkar and collaborators from BITS-Pilani: Ashis Kumar Pal and Tapomoy Guha Sarkar]

Predictions for measuring the 21-cm multi-frequency angular power spectrum using SKA-Low

Considering observations of the EoR 21-cm signal with futuristic telescope like SKA-LOW, Anjan Sarkar and collaborators have carried out a Fisher matrix based analysis for making predictions for measuring the multi-frequency angular power spectrum. The analysis has shown that it is possible to measure the multi-frequency angular power spectrum at a statistical significance level of $5-\sigma$ or more at angular scales $l \sim 1300$ with a total of 128 observing hours and the bandwidth, B = 44 MHz. This work is published in the Journal of Monthly Notices of the Royal Astronomical Society (MNRAS).
[Rajesh Mondal (University of Sussex, UK), Abinash Kumar Shaw (IIT Kharagpur), Ilian T. Iliev (University of Sussex, UK), Somnath Bharadwaj (IIT, Kharagpur), Kanan K. Datta (Presidency University, Kolkata), Suman Majumdar (IIT, Indore), Anjan K. Sarkar, Keri L. Dixon (NYU, Abu Dhabi)]

Observational Astronomy

It would come as a surprise to many if you tell them what the human eye sees of the night sky is just a very small portion of what is really coming to us from the heavens above. The reason being that the human eye is sensitive to just one small portion of the much larger panorama called the electromagnetic spectrum, which includes gamma rays, x-rays, ultraviolet, microwave and radio waves. On a fundamental level the above different forms of radiation are all the same, the difference lies in the frequency and wavelengths of the electromagnetic signal. The universe talks to us over the entire electromagnetic spectrum and the innate curiosity of the human mind would want to devise ways to listen. Astronomers have in fact built specialized telescopes designed to "see" in different frequency bands of radiation. RRI has been involved in designing and constructing Radio and X-ray telescope facilities both nationally and internationally - for example the Murchison Widefield Array (MWA), a precursor to the SKA telescope, which is a megaproject of the nation, and ASTROSAT, a multi institutional collaborative satellite mission launched by ISRO - which they routinely use to study cosmic objects of interest.

Radio Astronomy

The frequency-dependent behaviour of subpulse drifting: Carousel geometry and emission heights of PSR B0031-07

The carousel model of pulsar emission attributes the phenomenon of subpulse drifting to a set of discrete sparks located very near the stellar surface rotating

around the magnetic axis. Avinash Deshpande along with collaborators S. J. McSweeney, N. D. R. Bhat, S. E. Tremblay and G. Wright have shown that B0031-07's three drift modes can be understood in terms of a single carousel rotation rate if the number of sparks is allowed to change by an integral number, and where the different drift rates are due to (first-order) aliasing effects. This also results in harmonically-related values for P3 (the time it takes a subpulse to reappear at the same pulse phase), which was confirmed for B0031-07. They also investigated the frequency dependence of B0031-07's subpulse behaviour and extended the carousel model to include the dual effects of aberration and retardation, including the time it takes the information about the surface spark configuration to travel from the surface up to the emission point. Assuming these effects dominate at B0031-07's emission heights, conservative emission height differences for different modes as seen between 185 MHz and 610 MHz were derived. This new method of measuring emission heights provides a potentially strong test of the carousel model.
[From Curtin University, Australia: S. J. McSweeney, N. D. R. Bhat and S. E. Tremblay, G. Wright (University of Manchester, UK)and Avinash Deshpande]

Towards Low Frequency Observations of Radio Sky using Earth-based Setup

The very low-frequency radio sky (below 20 MHz) has not yet been explored adequately mainly because of the Ionospheric cutoff itself, except for some attempts from certain special locations on the Earth. Since the Ionospheric cutoff frequency is dictated by the Solar activity, there would be opportunities to make Earth-based observations at such low frequencies when the cutoff frequency reduces, such as during the nights and more so during Solar minima. In view of the recent claims regarding onset of Maunder like Solar Minimum beyond Cycle 25, Avinash Deshpande, Vinutha Chandrashekar, H A Aswathappa along with collaborator Pavan Uttarkar embarked on developing a suitable setup to attempt sky measurements in the low frequency window of 2-20 MHz at the Gauribidanur Field Station, using a specially designed Inverted Bowtie antenna, along with an available receiver chain. The expected antenna temperature was estimated from simulated brightness distribution using available sky maps at higher frequencies, and compared with results from observations. In interpreting the apparent variation in intensity as a function of time to estimate the underlying sky brightness pattern, GPS-based measurements of Total Electron Content (TEC) was used to estimate and account for the ionospheric imprint, in terms of frequency dependent absorption and its variation in time.
[Pavan Uttarkar (SIT, Tumkur), Vinutha Chandrashekar, H A Aswathappa and Avinash Deshpande]

Galactic distribution of pulsars

Efforts to conduct a full-scale simulation of pulsar population, aimed to study the distribution of pulsars were continued by Avinash Deshpande and Reshma Alexander a visiting student at RRI. Instructive tests were conducted to critically assess the initial simulation results.
[Reshma Alexander (NIT, Trichy) and Avinash Deshpande]

Studying the Circumstellar envelope of CRL 2688

Sahai et al. (1998 ApJ 493p301) imaged the EGG Nebula (CRL 2688) with WFPC2/HST. Their NIR image showed complex structure of the envelope tracing the history of AGB/Post–AGB Giant Branch Mass Loss. Molecular Line Surveys of this Carbon-rich Protoplanetary Nebula, AFGL 2688, performed in the 3 mm and 1.3 mm windows showed rich chemistry in its envelope (Zhang et al. 2013 ApJ 773p71). Earlier CO(J=2-1) image using the Plateau de Bure interferometer (1.07" x 0.85" beam size) by Cox et al (2000 A&A 353L25) shows multiple molecular outflows in AFGL 2688 correlating with the NIR features. The moderate beam size allowed only partial resolution of the bright CO clumps at the intersecting spots of the NIR rings and bipolar lobes, showing hints of interaction between the fast and slow winds. Since the spacing between the rings is <1", a higher angular resolution observation will facilitate understanding the progressive change of the interaction.

In collaboration with Nimesh Patel, Mohit Sinha and Ramesh Balasubramanyan are studying the interaction between the fast and slow winds of the Egg Nebula (AFGL 2688; CRL 2688), a well-known proto- planetary nebula, in order to compare the molecular observations with a binary-induced spiral shell model. Recent data collected with SMA in compact configuration is being analysed while extended configuration data is being awaited.
[Mohit Sinha, Nimesh Patel (CfA, Harvard, USA) and Ramesh Balasubramanyan]

Tracing the Dynamical Mass in Galaxy Disks Using HI Velocity Dispersion and Its Implications for the Dark Matter Distribution in Galaxies

A method to derive the dynamical mass of face-on galaxy disks using their neutral hydrogen velocity dispersion was developed during the past year by K S Dwarakanath and collaborators Mousumi Das, Stacy S. McGaugh, Roger Ianjamasimanana and James Schombert. This method was applied to nearby, gas-rich galaxies that have extended atomic Hydrogen gas disks and low inclinations. The galaxy sample included four large disk galaxies, NGC 628, NGC 6496, NGC 3184, and NGC 4214, and three dwarf galaxies, DDO 46, DDO 63, and DDO 187. Archival

atomic Hydrogen data from The HI Nearby Galaxy Survey (THINGS) and the LITTLE THINGS survey was used to derive the HI gas distributions and Spitzer mid-infrared images to determine the stellar disk mass distributions. Examination of the disk dynamical and baryonic mass ratios in the extreme outer disks where there is HI gas but no visible stellar disk has revealed that for the large galaxies, the disk dynamical and HI gas mass surface densities were comparable in the outer disks, whereas in the smaller dwarf galaxies, for which the total HI gas mass dominates the stellar mass, the disk dynamical mass was much larger than the baryonic mass. The authors propose that for these galaxies, there must either be a very low-luminosity stellar disk which provides the vertical support for the HI gas disk or there is halo dark matter associated with their disks, which is possible if the halo has an oblate shape so that the inner part of the dark matter halo is concentrated around the disk. The results emanating from this study are important for explaining the equilibrium of HI disks in the absence of stellar disks and is especially important for gas-rich, dwarf galaxies that appear to have significant dark matter masses associated with their disks.

[Mousumi Das (IIA, Bengaluru), Stacy S. McGaugh (Case Western Reserve University, USA), Roger Ianjamasimanana (Rhodes University, South Africa), James Schombert (University of Oregon, USA), and K. S. Dwarakanath]

Passive spirals and shock influenced star formation in the merging cluster A3376

Motivation:

Merging galaxy clusters serve as unique laboratories to study large-scale dynamic events which act on the constituent ICM and the galaxies within. While the effect of such merging activity on the ICM is heavily studied in X-ray and radio wavelengths, the cumulative effect on the evolution of the cluster galaxy population is largely unexplored. With such massive systems still being discovered, majorly through overdensities associated with X-ray anistropies and diffuse radio emission, analysing the effects of merger shocks on cluster galaxies warrants a multiwavelength approach targeting different aspects of galaxy evolution in transforming environments. With this big picture in mind, Kshitija Kelkar and K S Dwarakanath and collaborators have proposed a multiwavelength analysis of galaxy population in a particularly unique merging cluster system of A3376 at $z \sim 0.046$. This cluster underwent merger ~ 0.6 Gyrs ago, and is characterised by a strong X-ray hotspot with twin radio relics near the travelling shock front (Urdampilleta et al. 2018, Kale et al. 2012, George et al. 2015). This whole work is being conducted as a collaborative effort between several international groups, from whom data has been obtained.

They undertook a detailed analysis of star formation properties of galaxies in a nearby (red- shift approx. 0.046) young (approx. 0.6 Gyr) post-merger cluster system A3376, with a moderate shock front (shock velocity approx. 1630 km/s) observed as symmetric radio relics. Exploiting the spectroscopic data from the wide-field OmegaWINGS survey and the associated photometric information, their investigations have revealed the plausible effects of the dynamic post-merger environment differing from the putative pre-merger cluster environment. The remnants of the pre-merger relaxed cluster environment were realised through the existence of passive spiral galaxies located in the central regions of the cluster between the two BCGs. The analysis revealed that A3376 contains a population of massive (M(stars) greater than 10M(Sun)) blue regular star-forming spirals in regions of maximum merger shock influence but exhibiting star formation rates similar to those in relaxed clusters at similar epoch and low-mass (M(star) less than 10M(Sun)) late-type blue PSBs which could either be formed as a result of rapid quenching of low-mass spirals following the shock-induced star formation or due to the intense surge in the ICM pressures at the beginning of the merger. With the possibility of the merger shock affecting high- and low-mass spirals differently, these results bridge the seemingly contradictory results observed in known merging cluster systems so far and establish that different environmental effects are at play right from pre- to post-merger stage.

[Kshitija Kelkar, K. S. Dwarakanath, Bianca M. Poggianti (INAF, Italy), Alessia Moretti (INAF, Italy), Rogerio Monteiro- Oliveira (University of Sao Paulo, Brazil), Rubens Machado (UTFPR, Brazil), Gastao Lima-Neto (University of Sao Paulo, Brazil), Jacopo Fritz (UNAM, Mexico), Benedetta Vulcani (INAF, Italy), Marco Gullieuszik (INAF, Italy), Daniela Bettoni (INAF, Italy)]

Atomic Hydrogen in Galaxies during the Epoch of Galaxy Assembly

The key processes in galaxy evolution are gas infall onto galaxies, from the circumgalactic medium or via mergers, to form neutral atomic hydrogen (HI), the conversion of neutral hydrogen from the atomic state to the molecular state (H2), and, finally, the conversion of H2 to stars. Understanding galaxy evolution thus requires one to understand the evolution of both the stars, and the atomic and molecular phases of neutral hydrogen, the primary fuel for star-formation, in galaxies. However, the intrinsic weakness of the hyperfine HI 21cm spectral transition, the main tracer of the HI content of galaxies, has meant that it has not hitherto been possible to measure the atomic gas mass of galaxies at high redshifts; this is a critical lacuna in our understanding of galaxy evolution. Recently, K S Dwarakanath, Shiv Sethi and collaborators Nissim Kanekar and Jayaram Chengalur have reported

upgraded Giant Metrewave Radio Telescope observations of the redshifted HI 21cm line in a large sample of star-forming galaxies which has allowed them to measure the average HI mass of star- forming galaxies at a redshift z approximately equal to 1, towards the end of the epoch of galaxy assembly. They obtained an average HI mass similar to the average stellar mass of the sample; this is very different from galaxies of similar stellar masses in the local Universe, where the average HI mass is less than half the average stellar mass. However, it was found that the HI mass can fuel their observed starformation rates for only about 1 to 2 billion years in the absence of fresh gas infall. This suggests that gas accretion onto galaxies at z ~1 may have been insufficient to sustain high starformation rates in star-forming galaxies; this is likely to be the cause of the decline in the cosmic star-formation rate density after the epoch of galaxy assembly.
[Aditya Chowdhury (NCRA, Pune), Nissim Kanekar (NCRA, Pune), Jayaram Chengalur (NCRA, Pune), Shiv Sethi and K.S. Dwarakanath]

Tracing the Evolution of Ultraluminous Infrared Galaxies into Radio Galaxies with Low Frequency Radio Observations

K. S. Dwarakanath and collaborators Sumana Nandi and Mousumi Das have studied radio observations of ultraluminous infrared galaxies (ULIRGs) using the Giant Metrewave Radio Telescope (GMRT) combined with archival multifrequency observations to understand whether ULIRGs are the progenitors of the powerful radio loud galaxies in the local Universe. ULIRGs are characterized by large infrared luminosities (greater than 10^{12} L_{sun}), large dust masses (10^{8} M_{sun}) and vigorous star formation (10-100 M_{sun} per year). Studies show that they represent the end stages of mergers of gas-rich spiral galaxies. Their luminosity can be due to both starburst activity and active galactic nuclei (AGN). A sample of 13 ULIRGs that have optically identified AGN characteristics with 1.28 GHz GMRT observations were included in the study. Their aim was to resolve any core-jet structures or nuclear extensions and hence examine whether the ULIRGs are evolving into radio loud ellipticals. Their deep, low frequency observations show marginal extension for only one source. However, the integrated radio spectra of 6 ULIRGs showed characteristics that are similar to that of GPS/CSS/CSO/young radio sources. The estimated spectral ages are 0.4 to 8 Myr indicating that they are young radio sources and possible progenitors of radio galaxies. Through this study, the authors conclude that although most ULIRGs do not show kpc scale extended radio emission associated with nuclear activity, their radio spectral energy distributions do show signatures of young radio galaxies.
[(Sumana Nandi (NCRA, Pune), Mousumi Das (IIA, Bengaluru) and K S Dwarakanath)]

21cm power spectra using LOFAR

During a three month visit to ASTRON as a summer researcher, Jishnu Nambissan worked on the power spectrum aspects of the 21cm signal research. With Andre Offringa he measured the power spectra, which is the power in the signal at various angular scales, using the LOFAR instrument and analysed data from observations of one the fields close to the north celestial pole (NCP).
[Jishnu Nambissan, Andre Offringa and rest of the LOFAR EoR group]

X-ray Astronomy

Compact X-ray binaries are composed of a compact object, a neutron star or a black hole and a companion 'normal' star. The intense gravitational field of the neutron star causes matter from the companion star to accrete onto the neutron star, producing X-rays. X-ray astronomy is a powerful tool to study such objects. A plethora of information about system parameters like magnetic field geometry and strength, chemical composition of the surrounding medium and dynamics like orbital period and radius evolution of X-ray binaries, structural evolution of the accretion disk and its time scales, and structure in the stellar winds can be obtained by a careful analysis of the X-ray output from compact X-ray binaries. Research is also towards studying Cataclysmic Variable systems and Ultra-luminous X-ray sources using data from various X-ray observatories. A brief overview of various aspects of X-ray sources investigated by RRI astronomers during 2019-20 is given below.

Investigation of various aspects of compact X-ray sources

Superorbital modulation in SMC X-1 and a warped precessing accretion disc

Broadband spectral-timing analysis of the high mass X-ray binary pulsar SMC X-1 at different intensity states of its super-orbital variation using 10 Suzaku and 6 NuSTAR observations were carried out by Biswajit Paul and collaborators Pragati Pradhan and Chandreyee Maitra. The spectrum in all the states can be described by an absorbed power-law with a high energy cutoff and a black-body component along with an iron emission line. Compared to other supergiant HMXBs, the Fe K line equivalent width was found to be low in SMC X-1 - from less than 10 eV in high state to up to 270 eV in the low states. The spectral shape was found to be dependent on flux with the hard X-ray spectrum steepening with increasing flux. They also found a highly variable normalization of the power-law component

across these 16 super-orbital states. Pulsations in the hard X-rays for both the instruments were detected in all but two observations. The pulse profiles were near sinusoidal with two peaks and the relative intensity of the second peak decreasing with decreasing luminosity suggesting that the super-orbital modulation in SMC X-1 is not caused by absorption in precessing warped accretion disc alone and there are intrinsic changes in X-rays emanating from the neutron star at different super-orbital states. A putative cyclotron line at ~50 keV in the NuSTAR spectra of three bright states was found, indicating a possible magnetic field of 4.2 x 10^{12} G. Finally, with the new pulse period measurements resulting from this study, the time base for the secular spin-up of SMC X-1 was increased by thirteen years and the complete pulse period history showed a sudden change in the spin-up trend around 1995.
[Pragati Pradhan (Massachusetts Institute of Technology, USA), Chandreyee Maitra (Max Planck Institute For Extraterrestrial Physics, Germany), and Biswajit Paul]

Investigating a unique partial eclipse in the high-mass X-ray binary IGR J16393-4643 with Swift-XRT

The orbital profile of the high-mass X-ray binary IGR J16393-4643 shows a dip in its X-ray intensity, which was previously interpreted as an eclipse. Unlike most eclipsing HMXBs, where the X-ray eclipses are about two orders of magnitude fainter compared to the out-of-eclipse emission, this particular eclipse-like feature is narrow and partial, casting doubt if it is indeed an eclipse. To further investigate the nature of this low-intensity orbital phase, Biswajit Paul, his PhD student Sanhita Kabiraj and collaborator Nazma Islam used a large number of observations with Swift-XRT, covering the entire orbital phase. The soft X-ray observations also showed this low-intensity phase, which is about 30% of the intensity during rest of the orbit. They also carried out orbital-phase-resolved spectroscopy to compare the change in the spectral parameters inside and outside of this low-intensity state. Their results indicate that this low-intensity state might not be an eclipse, as previously thought but absorption in the stellar corona. The inclination angle of the binary for grazing eclipse caused by the stellar corona was also computed as part of this study.
[Sanhita Kabiraj, Nazma Islam (Harvard & Smithsonian, USA), and Biswajit Paul]

Probing Clumpy Wind Accretion in IGR J18027-2016 with XMM-Newton

Supergiant X-ray binaries usually comprise a neutron star accreting from the wind of an OB supergiant companion. They are classified as classical systems and supergiant fast X-ray transients (SFXTs). The different behavior of these subclasses of sources in X-rays, with SFXTs displaying much more pronounced variability, is usually (at least) partly ascribed to different physical properties of the massive star's clumpy stellar wind. In the case of SFXTs, a systematic investigation of the effects of clumps on flares/outbursts of these sources has been investigated exploiting the capabilities of the instruments on board XMM-Newton to perform a hardness-resolved spectral analysis on timescales as short as a few hundreds of seconds. Biswajit Paul and collaborators Pragati Pradhan, Enrico Bozzo, Antonis Manousakis and Carlo Ferringo have used six XMM-Newton observations of IGR J18027-2016 to extend the above study to a classical supergiant X-ray binary and compared the findings with those derived in the case of SFXTs. As these observations of IGR J18027-2016 spanned different orbital phases, they also studied its X-ray spectral variability on longer timescales and compared their results with previous investigations. Although obtaining measurements of the clump physical properties from X-ray observations of accreting supergiant X-ray binaries has already proven to be challenging, this study has shown that similar imprints of clumps are found in the X-ray observations of the SFXTs and at least one classical system, i.e., IGR J18027-2016. This study provides interesting perspectives to further extend this study to many XMM-Newton observations already performed in the direction of other classical supergiant X-ray binaries.
[Pragati Pradhan (Pennsylvania State University, USA), Enrico Bozzo (University of Geneva, Switzerland), Biswajit Paul, Antonis Manousakis (University of Sharjah, UAE), and Carlo Ferringo (University of Geneva, Switzerland)]

Cataclysmic Variable systems and ultra-luminous X-ray sources

With his PhD students Anirban Dutta and Tanuman Ghosh, Vikram Rana is working on several Cataclysmic Variable (CV) systems and Ultra-luminous X-ray sources (ULXs) utilizing data from the NuSTAR, XMM-Newton and other X-ray observatories.
[Anirban Dutta, Tanuman Ghosh and Vikram Rana]

Joint XMM-NuSTAR study of the dwarf nova SS CYG during its quiescence and outburst states

SS Cyg is one of the brightest dwarf nova containing a white dwarf and a main sequence secondary star, with an orbital period of 6.6 hrs. It undergoes outbursts every 40-50 days that lasts for about 10-12 days. Contrary to optical luminosity, the outburst phase is X-ray faint and quiescent phase is X-ray bright. It happens due to the change in geometry and properties of the accretion disc and X-ray emitting boundary layer (BL) region of the disc becoming optically thick to its own radiation in outburst phase. During the past year, Vikram Rana and his PhD student Anirban Dutta and Koji Mukai have used simultaneous

X-ray data from XMM and NuSTAR observatories covering 0.3-50 keV energy range in two phases of SS Cyg to study the change in geometry and properties of the accretion disc during the two states. The high sensitivity of NuSTAR and excellent energy resolution of XMM enabled the determination of various system components with unprecedented accuracy. They found that the maximum plasma temperature in quiescent phase, 25.1+/-3.2 keV , is significantly higher than that in outburst, 9.4+/-0.6 keV. Thanks to NuSTAR's high sensitivity in hard X-rays, they have conclusively confirmed the presence of the reflection hump in 10-30 keV range for both the phases, which arises when X-ray photons hit a relatively cold slab of the materials and undergo inverse Compton scattering. The differences in the reflection parameters enabled them to infer the change in location, geometry and properties of the BL region between two phases. Using XMM's excellent energy resolution the components of Fe K alpha emission were resolved. From the comparative study of line broadening of different components (6.4 keV, 6.7 keV, 6.9 keV) of Fe K alpha emission, one can learn about X-ray reflection, as well as the movement of the disc material during outburst phase.
[Vikram Rana, Anirban Dutta, Koji Mukai(GSFC/NASA, USA]

Super-Eddington accretion onto a stellar mass ultraluminous X-ray source NGC 4190 ULX1

A ULX in galaxy NGC 4190 was studied to learn about its X-ray characteristics by Vikram Rana and his student Tanuman Ghosh. This source was observed three times with XMM-NEWTON and six times with Swift. A clear cutoff was detected in NGC 4190 ULX1 spectra which rules out the interpretation of the ULX to be a black hole in a standard low/hard state. They report that the high quality EPIC spectra can be better described by broad thermal component, such as a slim disk or a Keplerian disk with optically thick Comptonizing corona. The spectra of NGC 4190 ULX1 may be associated with the classification of ``broadened disk'' with a ``curved'' state. The spectral curvature and downturn around 2-6 keV is explained by various models which manifest ``ultraluminous state'' of ULX. In case of accretion rates of the disk higher than Eddington limit, the state is known as super-Eddington state. In this case, it was found that the outward radiation pressure increases the scale height of the innermost part of the disk and here advection becomes significant. As a consequence, the radial temperature profile goes as $T(r) \propto r^{-p}$, where p, is the free parameter ($p \leq 0.75$) which takes the value of 0.75 in case of standard Shakura-Sunayev thin Keplerian disk. The preference of ``slim disk'' model over the thin disk model in the spectra clearly showed that the disk emission is super-Eddington in nature. In addition, they found long term spectral and flux variability of the source using XMM and Swift data. Clear anti-correlation between flux and power-law photon index was found which further confirmed the unusual spectral state evolution of the ULX. The unusual spectral states of the ULX source suggest that the source is in ``ultraluminous state'' with luminosities about 3-10 x 10^{39}ergs/sec. The positive luminosity -temperature relation further suggested that the multi-color disk model follows the $L \propto T^4$ relation which is expected for a black body disk emission from a constant area and slim disk model follows $L \propto T^2$ relation consistent with an advection dominated disk emission. From the broadened disk like spectral feature at such luminosity, when the upper limit of the mass of the central compact object from the inner disk radius and temperature was estimated it was found that the ULX hosts a stellar mass compact object for highest possible spin of a black hole in real astrophysical scenario.
[Vikram Rana, Tanuman Ghosh, Dominic Woltan (Institute of Astronomy, UK)]

Experimental Astronomy

Apart from carrying out observational astronomy with facilities, RRI astronomers do in fact built specialized telescopes designed to "see" in different frequency bands of radiation with focus on specific unsolved problems. The unrelenting quest for pushing the frontiers of knowledge about the observable universe and the need to see hitherto hidden regions of space has fuelled the need for better, efficient and sensitive telescopes and associated receivers and algorithms. AA research at RRI over the past year has focused on both these aspects and RRI astronomers and engineers have been involved in designing and constructing Radio and X-ray telescopes both nationally and internationally: the X-Ray polarimeter payload called POLIX, poised to be the first dedicated X-ray polarimeter mission in space, a precision radiometer called SARAS operating in the 40-230 MHz radio band dedicated to detecting spectral distortions in the cosmic radio background, PRATUSH, a proposed radiometer in lunar orbit that will reveal the Cosmic Dawn of our Universe an Efficient Linear Array Imager, a Supernova Search Engine, both operating at Radio wavelengths, and the Sky Watch Array Network (SWAN) that primarily aims at exploring the transient radio sky. Additionally, this aspect of astronomy research at RRI includes new methods and modelling aimed at extracting the signal of interest from confusing foregrounds and backgrounds.

Epoch of Reionization

Observation of high redshift Universe is the key to unfolding some of the long-standing questions in astronomy. One of such questions pertains to formation of first stars and

galaxies (Cosmic Dawn) and the subsequent reionization of the intergalactic medium (Epoch of Reionization). Given that this epoch is observationally poorly constrained there is very little information on the nature of the first sources of radiation, timing of their emergence and evolution, and the mechanism of the reionization. 21-cm from neutral hydrogen is one of the most-inclusive probe to study these epochs. Since the rest frame frequency of the signal is 1.42 GHz, radiation from each epoch is redshifted to a different frequency, and hence 21-cm provides a direct picture of each time slice. By measuring the brightness temperature of 21-cm radiation at different redshifts (and hence frequencies), one can constrain astrophysical parameters related to properties of first stars and galaxies.

Another unsolved mystery is the presence of dark energy that constitutes 68% of the total energy in the Universe, and accelerates its expansion. Though there are many theoretical models proposed to explain it, there are no observations to distinguish between these models. One of the promising tools to probe the nature of dark energy is to measure baryon acoustic oscillation (BAO). They are density fluctuations in the baryonic matter caused by sound waves in the primordial plasma and can be measured by tracing neutral hydrogen at large scales. By measuring BAO at different redshifts (especially z ~1-2), we can estimate the expansion history and constrain dark energy models. Since 21-cm radiation traces the matter at large scales, producing an intensity map of 21-cm is a promising way to measure BAO scale at different redshifts and hence constrain dark energy models.

Mayuri S Rao, Saurabh Singh, Jishnu Nambissan, Ravi Subrahmanyan, Udayashankar N, other members of the CMB distortions lab, Electronics Engineering Group, Mechanical Engineering Services at RRI and international collaborators are associated with different experiments that aim to detect the 21-cm signal from neutral hydrogen to understand the above periods of the evolution of Universe better.

PRATUSH

Probing ReionizATion of the Universe using Signal from Hydrogen is a proposed radiometer in lunar orbit that will reveal the Cosmic Dawn of our Universe. Observing the radio sky over 30-220 MHz over the far-side of the moon with high sensitivity, PRATUSH will answer the question of when the first stars formed in our universe, the nature of the first stars, and what was the light from the first stars or, in other words, the colour of the light of Cosmic Dawn. PRATUSH will be the pioneering space telescope that will reveal, for the first time, the history of our infant Universe as it transformed after the Big Bang - from cold gas into stars and galaxies and the universe as we know it today. PRATUSH, as its name denotes, will inform us of the first rays of the first suns in the infant Universe. The proposal for PRATUSH was submitted jointly by members of RRI CMB DISTORTION Lab in response to an announcement of opportunity for science payloads from ISRO. PRATUSH has been funded by ISRO for pre-project studies mode over 2019-2020, with an expectation of continued funding for a second year of pre-project studies.

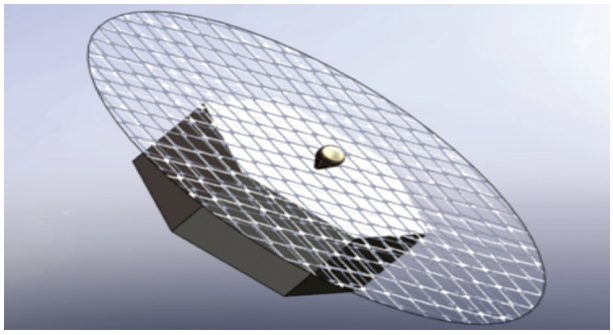


Figure 1. A conceptual design of PRATUSH : Probing ReionizATion of the Universe using Signal from Hydrogen is a proposed radiometer in lunar orbit that will reveal a wealth of information about the first stars and galaxies in our Universe. PRATUSH was proposed by members of RRI CMB DISTORTION Lab in response to an announcement of opportunity for science payloads from ISRO. PRATUSH has been funded by ISRO for pre-project studies mode over 2019-2020.

PRATUSH-Chandrayaan3 (Epoch of Reionization)

Probing ReionizATion of the Universe using Signal from Hydrogen on Chandrayaan-3, is a custom designed precision spectral-radiometer that will measure the low-frequency radio sky over 55-110 MHz with an aim to detect the redshifted 21-cm signal from the Cosmic Dawn (CD). PRATUSH-C3 aims to achieve the sensitivity required to detect this faint and information rich cosmological signal by operating in the radio quiet environment in the far side of the moon occulted from Earth- and Sun-shine. Over three months spanning Feb-April 2020, PRATUSH efforts were focussed on developing a payload that could be accommodated within the technical and schedule constraints of the Chandrayaan-3 mission. Tremendous progress has been made jointly by RRI and SAC teams towards designing and optimizing the payload concept. The PRATUSH-C3 experience has provided valuable lessons towards designing PRATUSH as a payload for a future mission, with the most valuable resource coming in the form of tight-knit interactions between RRI and ISRO (SAC) teams. The stringent constraints on power, mass, volume, of the payload imposed by the already mature design of the Chandrayaan-3 Propulsion Module were found to be in contradiction to those driven by the science requirements of PRATUSH-C3.

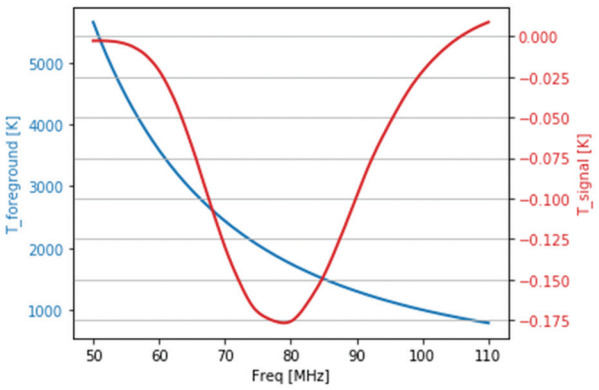


Figure 2. The redshifted-21 cm signal from the Cosmic Dawn as predicted by one of the several theoretical models allowed in the parameter space of standard astrophysics and ΛCDM cosmology is shown in red. In blue is the 'foreground' additive contaminant to signal detection, dominated by galactic synchrotron emission. Note the difference in the scales of the spectra. Expressed in brightness temperature units as is the convention in radio-astronomy, the CD signal is *O*(0.1-0.1) Kelvin bright, the foregrounds are *O*(1000) Kelvin bright. By making a very sensitive measurement of the sky-radiation across frequency, or sky-spectrum, PRATUSH-C3 would distinguish between theoretical models and ultimately detect the signal.

[Saurabh Singh, Mayuri S Rao, Jishnu Nambissan and Members of the CMB DISTORTION Lab (including Emeritus Scientist S Seetha) and collaborators from SAC Ahmedabad, URSC, Bengaluru]

Square Kilometre Array (SKA)

The Square Kilometre Array (SKA) observatory is a mega-science project, which is recommended for funding by DST and DAE. Indian participation in the SKA includes but is not limited to the Low-Frequency Aperture Array, Telescope Manager, Central Signal Processor, Epoch of Reionization Science working group, to name a few. RRI is leading the effort to develop an RFSOC-based Integrated-Prototype (IP) for the SKA-Low digital receiver. The effort will primarily focus on building a Field Programmable Gate Array (FPGA) based digital receiver prototype with emphasis on collaboration between Indian industry and human-resources. This will serve as a demonstration of inhouse capability, technology and infrastructure development of the labs at RRI, and serve as a test bed for SKA- Low Frequency Aperture Array (LFAA) of the SKA- Low and serve as a model of development that can be scaled over the SKA construction phase. During the construction phase, RRI will be involved in two crucial engineering components of the SKA, namely the Low Frequency Aperture Array (LFAA) and the Central Signal Processing Pulsar Search Sub-element. The activities for bridging phase, the path forward for construction phase were laid out in 2019-2020.

[Mayuri S Rao, Prabu T, Saurabh Singh, Jishnu Nambissan, K Srivani, B S Girish, R Somashekar, A Raghunathan and collaborators from SKA India Consortium members led by Yashwant Gupta, NCRA]

Readout instrumentation for on-going and future CMB telescopes

The sensitivity requirements of upcoming and future Cosmic Microwave Background experiments can be largely increased by increasing the number of photon-noise limited detectors (typically transition edge sensor bolometers). Deploying O(1000-10,000) or more detectors in the receiver focal plane pose thermal, electrical, and noise challenges to detector readout technology. A promising upcoming readout technology for quantum noise limited detectors is the microwave SQUID multiplexer (mu-MUX) which combines the advantages of high-multiplexability of microwave Kinetic Inductance detectors (MKIDs) and the legacy of field demonstrated TES-detectors. Efforts by Mayuri S Rao and collaborators are towards studying and improving the noise performance of mu-MUX for CMB telescopes, quantum detectors with applications to quantum computing. This spans from cold-readout technology with designing and fabricating of low-loss superconducting Niobium microstripline gigahertz resonators, effective RF wiring with cryogenic linear low-noise amplification of resonator signals and high performance FPGA based firmware development for tone-tracked resonator detection algorithms. The Simons Observatory (SO) is an upcoming polarization-sensitive Cosmic Microwave Background (CMB) experiment which adopts mu-MUX readout technology to read signals from O(10,000) detectors in the 3 small aperture telescopes and one large aperture telescope. SO will deploy in a site in the Atacama desert in Chile and is expected to see first light in 2020. The CMB-S4 is the stage 4 next generation CMB telescope that will deploy O(500,000) background limited detectors to reach the highest targeted sensitivity to CMB polarization. mu-MUX is a contending readout technology in addition to time domain multiplexing (TDM), and frequency division multiplexing (DfMUX), for CMB-S4.

[Mayuri S Rao, Akito Kusaka (LBNL, USA), Aritoki Suzuki (LBNL, USA), Adrian Lee (U.C. Berkeley, USA), Zeeshan Ahmed (SLAC, USA), Suzanne Staggs (Princeton University, USA), Simons Observatory, Chile and CMB-S4 collaborations]

Experimental detection of 21cm signal from Cosmic Dawn and Epoch of Reionisation

The general theme of Jishnu Nambissan's research is to experimentally detect the redshifted 21cm signal from cosmic dawn and epoch of reionisation. When the first stars and galaxies form, they were expected to have heated and ionised the neutral hydrogen in the intergalactic medium. The evolution of the signal with time depends

on how much neutral hydrogen existed and how the 21cm transition coupled to the ambient via various mechanisms. A measurement of the signal, which is now expected to be in the frequency range of 40-250 MHz, will reveal the properties of those stars and galaxies. Jishnu's interest is specifically in the all-sky or global component, which in principle can be detected by a well calibrated single antenna based instrument.

However, owing to strong Galactic and extragalactic foregrounds at these frequencies, which are several orders of magnitude brighter as compared to the 21-cm signal, the detection is not a trivial task. Also the instrumental response can introduce confusing structures into the measured sky spectrum, thereby precluding a detection. In the past one year, he has concentrated on commissioning and deployment of SARAS-3 system, which is an experiment to detect the global 21-cm signal. The instrument now has been augmented with a new type of antenna that floats on water to avoid the deleterious effects of a lossy ground on system performance. Specifically, his efforts were towards (i) improving the calibration of the instrumentation used to measure the antenna characteristics, specifically the transfer function (return loss) (ii) mathematically modelling the system response and qualifying the system with lab measurements as well as deployments at some sites near to Bangalore (iii) along with Saurabh Singh, Jishnu is involved in detailed analysis of the data from the deployments with an aim to detect the 21cm signal.

Another research focus for Jishnu Nambissan and collaborators Benjamin McKinley and Cathryn Trott is towards detection of global 21cm signal using a different technique involving interferometry with closed space antennas.
[Jishnu Nambissan and collaborators from Curtin University, Australia: Benjamin McKinley and Cathryn Trott]

X-ray Polarimeter (POLIX)

X-ray polarimetry is an unexplored area in high energy astrophysics. X-ray polarization measurements can give valuable insights about (i) the strength and the distribution of magnetic field in the sources (ii) geometric anisotropies in the sources (iii) their alignment with respect to the line of sight and (iv) the nature of the accelerator responsible for energizing the electrons taking part in radiation and scattering. During the past few years, RRI has been designing and building an Indian X- ray polarimeter (POLIX), as a payload for a dedicated small satellite mission of ISRO called XPoSat.

During 2019-20, significant progress has been made towards completion of the Qualification Model (QM) and Flight Model (FM) of POLIX.

- Fabrication of the QM baseplate, scatterer and shield was completed
- Fabrication of the FM detector components, collimator, baseplate and most of the shield were completed.
- The QM, including two working detector modules and all other mechanical components were assembled and subjected to vibration at qualification level. Following the vibration tests, some reworks of QM and FM detectors have been taken up.
- The wiring work for four FM detectors have been carried out. Some further modifications are ongoing.
- PCB design, space qualified layout, layout review, have been completed for all 14 types of PCBs of POLIX. Laboratory models of all 14 types have been made, populated, and tested with commercial components.
- A total of 69 PCBs are being fabricated for QM and FM of POLIX.
- All QM and FM PCBs for front end electronics, total 30 in number, have been fabricated and tested successfully.
- Interface of the ground checkout system for POLIX has been tested with the PCBs.
- Significant progress has been made in software development for POLIX data reduction and analysis.

[P. V. Rishin, Vikram Rana, M. R. Golapakrishna, S. Krishnamurthy, Md Ibrahim, M. Hemant, Pooja Verma, Md. Irshad, Harikrishna Sahoo, G. Rajagopala, Nandini Sreeanand, T. S. Mamatha, P. Sandhya, Ashwin Devraj, Abhilash Kulkarni, Varun and many members of Mechanical Engineering Services have made major contributions to all the development works described above]

X-ray Optics

X-ray optics utilizes grazing incident of X-ray photons onto a conical mirror that is coated with thin layers of highly reflective material (Gold, Pt, W, Si etc.) and thereby focuses X-rays to a focal point. Focusing of hard X-rays have been extremely challenging task as the angle of incidence decrease with increase in the energy of photons. Focusing capability for hard X-rays (beyond 10 keV) has tremendous potential to open a new discovery window in high energy astronomy. Fabrication of such hard X-ray telescope is a very ambitious project and hence requires active collaboration with several national institutions . A collaborative effort has been initiated between RRI, PRL Ahmedabad and URSC, ISRO to develop technology for hard X-ray telescope. Vikram Rana is leading the RRI part where they will develop a novel technique for the precise assembly of thousands of segmented X-ray mirrors that will mostly decide on the scientific performance of

the telescope. As a first step towards demonstration of X-ray mirror assembly technique, they have designed and developed an automated epoxy dispensing machine (as shown below) for stacking flat glass mirrors using epoxy and precisely machined graphite spacers. It has 3-axis movement that is completely controlled by a computer with inhouse developed softwares.

In addition to full scale hard X-ray telescope they are also exploring Micropore Optics (MPO) for soft X-ray focusing. This option is significantly light weight compared to conventional optics which is very important requirement for space missions. Vikram Rana and collaborators are in the process of designing an experimental setup to characterise MPOs using existing 12- meter long X-ray beam line at RRI that was primarily developed for POLIX mission.

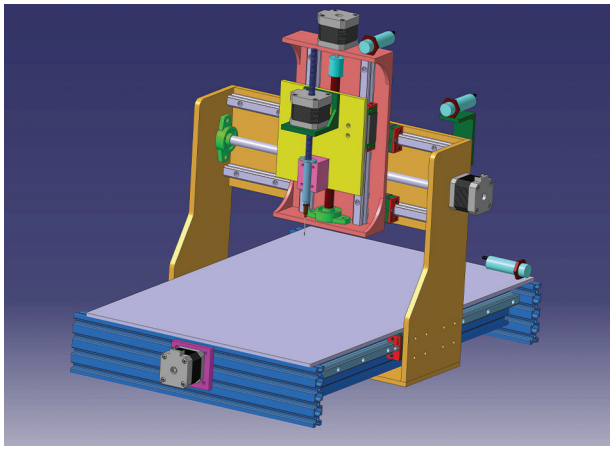


Figure 3. Automated epoxy dispensing machine for stacking flat X-ray mirrors
[Vikram Rana]

DAKSHA

Recently Vikram Rana became part of the DAKSHA X-ray observatory that is led by IIT, Bombay. Daksha is an ambitious project aiming to develop an all sky X-ray monitor with sensitivity 10 times better than any flown so far and having the ability to detect most of the X-ray counterparts of the NS-NS merger events likely to be detected by the next generation GW detectors in the 2021-2024 time frame. It is sensitive in a wide energy band of 1 keV to 1 MeV. The Daksha mission designed as a pair of identical satellites in opposing near-earth equatorial orbits, will detect and characterise the high energy counterparts of every gravitational wave event within the advanced LIGO range of 200 megaparsecs. DAKSHA will be using a large number of CZT detectors (more than ~1000) to achieve the required sensitivity and field of view. RRI will play a crucial role in testing, characterization and calibration of these detectors. Vikram Rana will be designing and developing the experimental setup for the research work on CZT detectors to use with the DAKSHA mission.
[Vikram Rana]

Indian SWAN

The Indian SWAN demonstrator system of 7-tiles located presently at the Gauribidanur Field Station has been made ready for relocation, after incorporating separate beamformer supply and control hardware/ software, as well as GPS-disciplined Rubidium frequency standard successfully. The SWAN Imaging Challenge 2019 concluded with 6 teams submitting entries, and the entry by the IISER-Mohali team (coordinated by Satyapan Munshi) was judged as the best effort. Students developed analysis software for processing the raw voltage sequences to the stage of obtaining reliable measurements of complex visibilities for the set of interferometry baselines, and using these to make synthesis images.
[Avinash Deshpande, C. Vinutha, K. B. Raghavendra, H. A. Aswathappa, P. Sasikumar, P. Uttarkar (SIT, Tumkur), some other colleagues from the EEG and RRI workshop and several student participants in SWAN, from the various institutes across India.]

Building the RRI Efficient Linear-array Imager prototype for molecular astronomy

RRI Efficient Linear-array Imager prototype ("An Efficient Linear-array Imager (ELI) for radio astronomy", 2014, MNRAS 444 p2212) is currently being built at RRI field station at Gauribidanur (Figure 4). The optics of this telescope demonstrates that one can trade instantaneous sensitivity with instantaneous field-of-view, while preserving the antenna throughput. The optics also involves cylindrical primary that promise economy.

During the past year, Sandeep H, Avinash Kotla, Sandeep K, Charles Paul, Technical consultant, RRI and Ramesh B have completed the following tasks:

- All joint parts made of stainless steel boxes and shoes have been made, finished and used in the assembly. This includes joint parts for the secondary support frame. They have all been made from SS sheets using laser cutting, CNC bending, spot welding and sheet metal work and processes.
- All aluminium tubes cut to required sizes have been assembled in to the structure. Required taps and drills have been made.
- A high precision laser sensor has been procured. A CMM using it has been made. Panel construction will be undertaken now after the completion of structure assembly.

- Antenna base civil structure has been built at the field station. Plummer blocks have been placed on the type II columns housing the bearings. Shaft and shaft joint parts have been made and integrated in to the assembly.
- A new gear system has been designed. A plastic version of it has been made and tested. Its performance has been satisfactory. Now, the components for the final gears have been ordered. Once they arrive, they will be assembled and integrated to the telescope structure along with its drives.

To demonstrate the working of ELI, a two channel receiver is also being built. Once demonstrated, the telescope will be equipped with 16 receivers and make 64 beams to undertake a spectral and continuum transit survey of the Galactic plane in the 7-11 GHz band. The ELI prototype project provides ample opportunity for many graduate students to be involved in technology development and thereby gain hands-on experience in doing high quality engineering.

Figure 4. (Left) A view of the ELI telescope backup structure **(right)** Another view. Note the structure includes the assembled backup space frame for both the primary and secondary.

[Sandeep H, Avinash Kotla, Sandeep K, Charles Paul, Technical consultant, RRI and Ramesh B]

Initial efforts for an Indian sub-millimeterwave astronomy facility

Over several years, discussion with SAC, ISRO regarding a sub-millimeterwave facility has been going on. It has led to SAC, ISRO deciding to build a 3m sub-millimeterwave telescope first and then to follow it with a 6m telescope. Both are likely to be located in Hanle, near the HCT. To facilitate ISRO-institutions interaction, RRI and ISRO organised a core group drawn from different institutions (TIFR, IIST, IIA, ISRO, RRI) and its first meeting was held at RRI on June 26, 2020. It was decided to organise a science meeting and form an Indian Sub-millimeterwave Astronomy Alliance, a body of organisations interested in mm-wave astronomy that would spearhead future pursuit of mm/sub-millimeterwave astronomy in India. ISRO and RRI jointly organized a science meeting of Indian astronomy community interested in millimeterwave studies during Jan 9 & 10, 2020. With 25 (of which 13 were away from Bangalore) participants and about 18 talks, the meeting was successful. Everyone expressed the need for such meetings as well as the telescope facilities in India to pursue submillimeter wave astronomy. Choosing a site in the Hanle area to facilitate observing the Galaxy and being part of EHT was essential. T.K.Sridharan and Ramesh Balasubramanyam travelled to Hanle during Jan 12-18 and chose two potential sites on behalf of the consortium for IIA and ISRO to jointly choose from.

Algorithms & Signal Processing

Research effort at the Institute is also focused on developing methods and algorithms that would detect the required signal from background or place useful constraints on the parameter space of theoretical models.

Maximum Entropy and Probability Distributions

Assuming entropy functions different from -p.log(p), investigations of maximum entropic probability density distributions (PDFs) by Avinash Deshpande and collaborator Albert Shaji has shown that for -log(p) entropy, the maximum entropic distribution is the Cauchy distribution, relevant as PDF only in certain range of characterizing parameters.

[Albert Shaji (Christ University, Kerala)and Avinash Deshpande]

Research: Knowledge Creation

Light and Matter Physics

Light and Matter Physics

Overview

Light and matter interaction is at the heart of how scientists learn about the physical properties of objects ranging in size from that of the universe down to atomic scales. At the Raman Research Institute members of the light and matter physics (LAMP) group are engaged in research on fundamental properties of electromagnetic (EM) waves and on the nature of interaction of EM waves with gaseous neutral atoms, ions, ultracold and exotic states of matter. The underlying theme of these studies is to unravel fundamental processes which will qualitatively improve our understanding of the studied phenomena and provide new guiding principles. The knowledge thus gained will help in utilization of these principles both at the fundamental and at the applied level.

Focus 2019-20

Ultracold Atoms, Molecules and Ions Research

One major area of research in the LAMP group involves the cooling and trapping of atoms, ions and molecules in order to study interactions at low temperatures.

Collisions and Interactions

Collisional cooling of trapped ions with cold atoms: results and insights

A series of experimental and numerical results has allowed Sadiq Rangwala, his PhD student Rahul Sawant and collaborator Sourav Dutta to propose and explain the mechanisms for collisional cooling of a trapped ion by sequential binary collisions with atoms. In their experiments, they studied the cooling of ions in hybrid atom-ion traps when the reservoir of the coolant atoms is spatially localized at the centre of the ion trap. Under these conditions the widely and long held expectation that for the ion to collisionally cool, the atom must be of lighter mass (i.e. $m_I > m_A$) is overturned. Instead they have shown ion cooling for $m_I < m_A$ in addition to $m_I > m_A$, and have explained why earlier work establishing mass ratios does not apply to the experiments in hybrid traps. Further, for cooling of an ion A^+ by the parent atom A, the mechanism of resonant charge exchange (RCE) allows for extremely efficient cooling of the ion A^+. They demonstrated this mechanism by comparing the cooling rate of an ion with a localized ensemble of its parent atoms and with a lighter atomic species, where in the latter case the RCE mechanism does not exist. They used the difference in measured cooling rates for a given number density of the atoms and the theoretically calculated difference between elastic and RCE cross sections to show that the cooling efficiency per collision with RCE is much greater than the cooling by elastic collision.
[Sourav Dutta (TIFR, Mumbai), Rahul Sawant and Sadiq Rangwala]

Interaction potentials and ultracold scattering cross sections for the $^7Li^+$- ^7Li ion-atom system

Sadiq Rangwala and his group members Amrendra Pandey, Niranjan Myneni, Nishant Joshi along with collaborators R. Vexiau and Olivier Dulieu have calculate the isotope independent $^7Li^+$-^7Li potential energy curves for the electronic ground and first excited states. They calculated the scattering phase shifts and total scattering cross section for the $^7Li^+$- ^7Li collision with emphasis on the ultra-low energy domain down to the s-wave regime. Using the effect of physically motivated alterations on the calculated potential energy curves to determine the bound of accuracy of the low-energy scattering parameters for the ion-atom system they found that: (i) scattering length for the $A_2\Sigma^+_u$ state, $a_u = 1325\ a_0$, is positive and has well constrained bounds. (ii) For the $X^2\Sigma^+_g$ state, the scattering length, $a_g = 20465\ a_0$ has a large magnitude as it is sensitive to the restrained change of the potential, due to the presence of a vibrational state in the vicinity of the dissociation limit.
[A. Pandey, M. Niranjan, N. Joshi, and S. A. Rangwala and collaborators from Université Paris-Saclay, France: R. Vexiau and O. Dulieu]

Measuring Quantum Interactions

Sadiq Rangwala wrote an article for Physics News wherein he introduced the need to study interactions between cold and trapped species of atoms, molecules and ions very carefully for an understanding of quantum many particle systems. The article described experiments at RRI devised to measure such interactions, namely hybrid trap experiments. Some results of interactions between trapped atoms and ions as well as non-destructive measurement of interactions using cavities were some of the topics discussed.
[Sadiq Rangwala]

Quantum Simulation of Condensed Matter Physics using Degenerate Gases

Status of the experimental facility to study Quantum Degenerate Mixture of Neutral Sodium and Potassium atoms

Overview:

Focus of Saptarishi Chaudhuri and his group members Sagar Sutradhar, Shreya Bagchi, Bidyut Bikash Boruah and Sanjukta Roy research at RRI is the setting-up of a new experimental system with mixtures of ultra- cold atom clouds with the long-term goal of investigating quantum degenerate polar molecules with tunable, long-range dipolar interactions to simulate complex condensed matter phenomena. Their approach is complementary to using quantum degenerate neutral atoms where interactions are introduced via short-range, isotropic s-wave scattering which limits the observation of many strong correlation effects.

During the past year efforts continued towards installing a new state of the art experimental facility to trap and cool neutral atoms to ultralow temperatures using Laser cooling and trapping techniques. In particular, they have developed and installed laser systems and other precision instruments to trap and cool two different species of alkali atoms – Sodium (Na) and Potassium (K) – simultaneously. These experiments have the long-term goal of investigating the emerging physics of quantum degenerate mixtures and polar molecules with tunable, long-range dipolar interactions to simulate complex condensed matter phenomena. In the previous year's annual report, Saptarishi Chaudhuri had provided details about the design of the vacuum system and installation and characterization of some of the laser systems and components. This year they have installed the ultrahigh vacuum system and obtained ultrahigh vacuum (less than 10^{-10} mbar) after pumping down.

The vacuum system consists of two high-flux sources of cold atomic beam in the form of two-dimensional magneto optical trap for both species of atoms. Atoms from the sources will be captured in a dual-species magneto optical trap (MOT) simultaneously. A magnetic transport stage was designed to simultaneously transport the trapped atoms in a moving magnetic trap over a distance of nearly a meter to a connected glass vacuum cell with large optical access and ultra-high vacuum. The photograph of the installed vacuum system is presented in Figure 1. Most of the vacuum components were either purchased or machined in RRI mechanical workshop. Ultra-high vacuum glass cells were designed inhouse and manufactured by an external vendor.

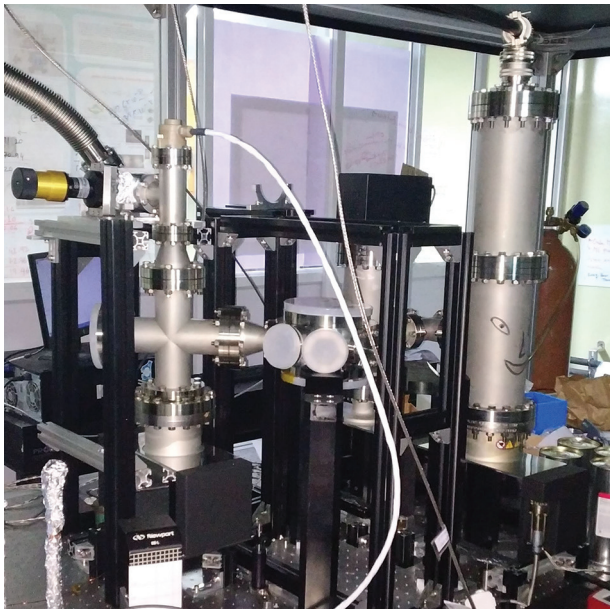


Figure 1. The Ultra-high vacuum system installed in Quantum Mixtures Laboratory
[Sagar Sutradhar, Shreya Bagchi, Bidyut Bikash Boruah, Sanjukta Roy and Saptarishi Chaudhuri]

Diffusion and response function of cold atoms in Magneto optical trap

During the past year Subhajit Bhar, Maheswar Swar, Sanjukta Roy and Saptarishi Chaudhuri have initiated a set of experiments to study the quantum diffusion law. This set

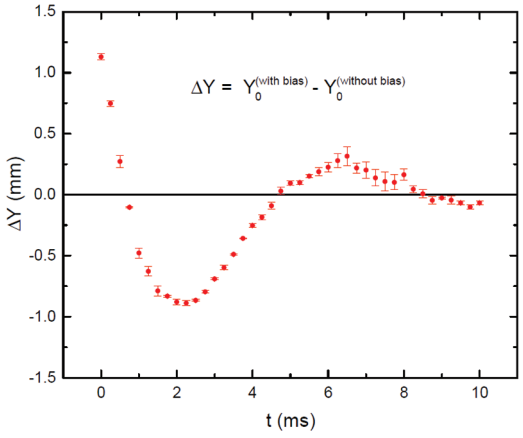


Figure 2. A typical motion of the cold atomic cloud. The relative displacement (ΔY) is the difference between the mean position of the cold cloud with and without bias field.

of measurements are motivated and supported by theory collaborators Supurna Sinha, Urbashi Satpathi and Rafael Sorkin. In this experiment, the cloud of ultra-cold atoms is allowed to diffuse in the presence of optical potential

and the diffusion rate measured by direct imaging of the atomic cloud. As a first step in the measurements, they displaced the cloud of cold atoms in a magneto optical trap using an external uniform magnetic bias field after which the external field was suddenly switched and the motion of the cloud was observed. A response function of the ultra-cold atoms from the measurements were extracted. A typical centroid motion of the atomic cloud as a function of time is shown in figure 2.

[Subhajit Bhar, Maheswar Swar, Supurna Sinha, Urbashi Satpathi (ICTS, Bengaluru), Rafael Sorkin(Perimeter Institute, Canada and Adjunct Professor, RRI), Sanjukta Roy, Saptarishi Chaudhuri]

Precision Atom-Light Interaction and Spectroscopy

Demonstration of phase-sensitive amplification of an optical field controlled by a microwave field

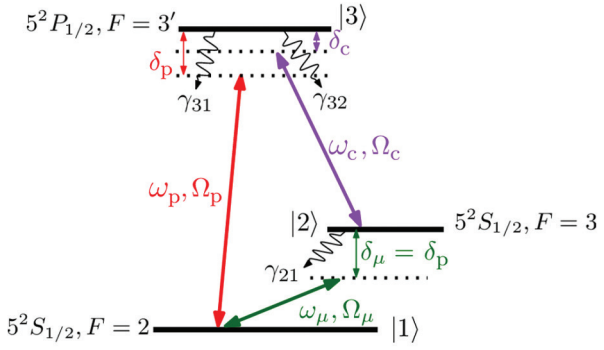


Figure 3. Three-level atom in a Delta configuration.

For the past 3-4 years Andal Narayanan and her students at the Quantum Optics lab have been experimentally studying an atom-light interaction scheme which involves light fields and dilute Rb atoms at room temperature. The atomic system connects optical and microwave fields through a non-linear interaction. During the past they had extracted experimentally this very interesting non-linear interaction mediated by the atom at low intensities of participating fields using the well-known phenomenon of electromagnetically induced transparency. Particularly, in the past three years, they have shown using such a system a fast, high-contrast optical switch controllable by the phase of a microwave field (Journal of physics B, volume 50 (16), Published 31 July 2017), generation of an optical field through microwave induced non-linear interaction (Opt. Lett., 44:33-36, Jan 2019). As a natural extension to the generation process, Andal Narayanan and her PhD students Asha K., Adwaith K. V. and Pradosh K N along with collaborators Barry Sanders and Fabien Bretenaker have studied the amplification (gain) of an input seed optical field controllable by the intensity and phase of microwave field. Such an amplification if realized will be coherent, phase sensitive and potentially will be a very good candidate for zero-noise-added amplification due to the underlying quantum properties of the amplification process. During the past year they achieved phase sensitive amplification of an optical field. The two main features of the amplification process namely, its microwave phase and intensity sensitive property is shown in the following graphs(Figure 4) This work is now published. (Opt. Express 27, 32111-32121 (2019))

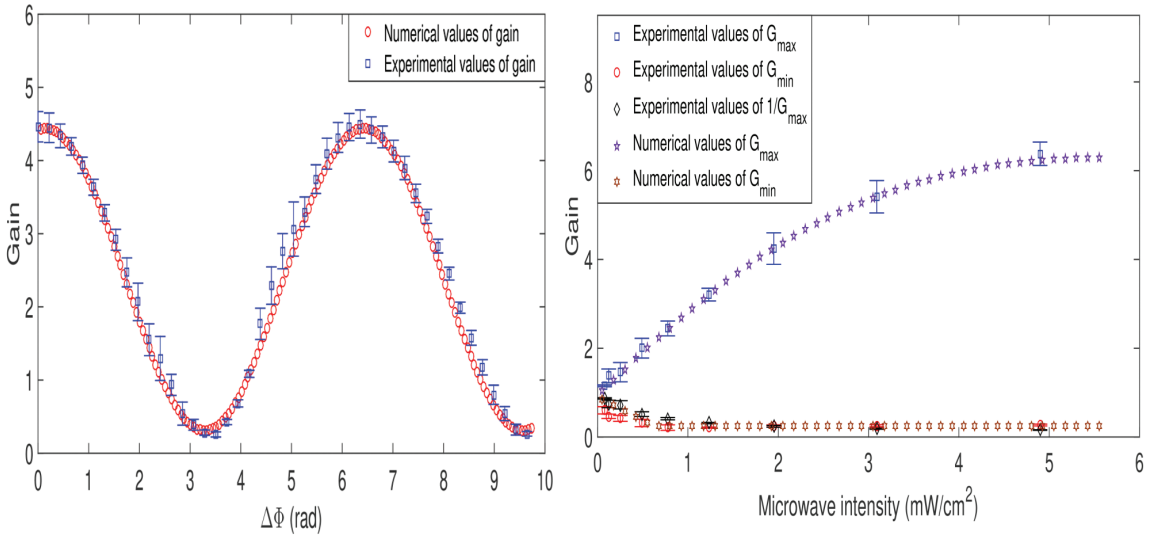


Figure 4 (Left) Gain of the optical field as a function of the phase of the microwave field. **(Right)** Maximum and minimum gain of the optical field plotted as a function of microwave intensity.

[Asha K. (Joint Ph.D student from Kuvempu University), Adwaith K. V., Pradosh K N, Andal Narayanan, Barry Sanders (University of Calgary, Canada) and Fabien Bretenaker (Laboratoire Amie Cotton, France)]

Slow light governed by atomic non-linearity: A theoretical investigation.

It is well known that during propagation of electromagnetic (EM) field inside a material medium the EM field suffers absorption and dispersion. A lot of theoretical and a few experimental works have addressed the problem of controlling the speed of propagation of a chosen EM field inside an atomic medium through manipulating the dispersive and absorptive properties of the atom by other EM fields. The success story of such endeavours have resulted in subluminal (slow) and superluminal (fast) propagation of an EM field inside a material medium controlled by the phase and intensity of another field (J. Opt. B: Quantum Semiclassical Opt. 7, 168 (2005) and Phys. Rev. A 63, 043818 (2001)). This has applications in communication in creating controllable optical delay lines. Such effects when realized with low intensities of EM fields interacting with few atoms can preserve coherence and thus are important platforms to carry quantum information with controllable speeds. The above mentioned studies all focus on controlling the propagation of light that has been initially sent into an atomic system.

In a recent theoretical study, Andal Narayanan and her students Saaswath J K, Adwaith K V and Pradosh K N investigated the possible control of propagation of a generated field through non-linear interaction of the atom with control fields. Specifically, using a three wave mixing which involves the $\chi(2)$ non-linearity of the delta system (Figure 3) they have elaborated how on modification of a specific scheme (Phys. Rev. A 70, 023813 (2004)), one can control the propagation of a generated optical pulse from subluminal to superluminal by changing the parameters of a frequency separated microwave drive field.
[Saaswath J K (Visiting student from IIT, Madras), Adwaith K V, Pradosh K N and Andal Narayanan]

Spin correlations in Raman pumped cold Rubidium atoms

Overview:

Previous work on measuring the spin correlations from neutral atoms by Maheswar Swar, Dibyendu Roy, Subhajit Bhar, Sanjukta Roy and Saptarishi Chaudhuri continued this year with the notable new result being detection of spin correlations in cold atoms. While the highlight of the previous research work was the demonstration of high precision magnetometry using spin noise measurements and non-perturbative detection of atomic population in different hyperfine states, by extending the observation in cold atoms, now, they have not only improved upon the magnetometry precision by two orders of magnitude but also demonstrated the potential of using this technique to measure quantum correlations.

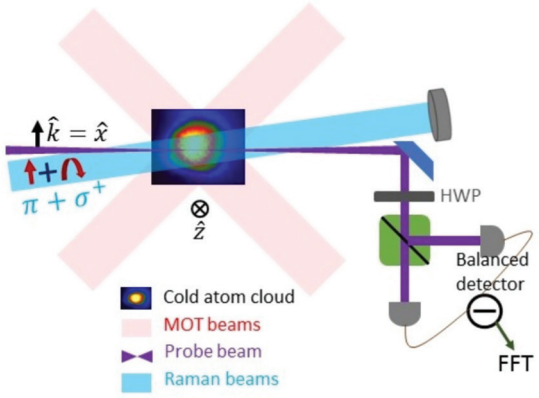


Figure 5. Schematic of in-situ spin correlations measurement using cold atoms. This cloud has been coherently driven by Raman beams during the experiment. A linearly polarized and far-detuned probe beam acquire the SN signal from in-situ cold atomic cloud.

In their experiments, they trapped and cooled ^{87}Rb atoms inside a vacuum chamber by means of magneto- optical trap (MOT). Whereas in their previous experimental set-up where spin correlation from the thermal atoms were detected, they had used a far off resonant linearly polarized probe laser beam through the atomic sample and measured the polarization fluctuation (or the fluctuation of the faraday rotation) of the probe beam, in the new set-up they added a pair of Raman laser beams to coherently drive the atoms between the magnetic sub-states. A typical correlation signal obtained from cold atoms is shown in figure 6.

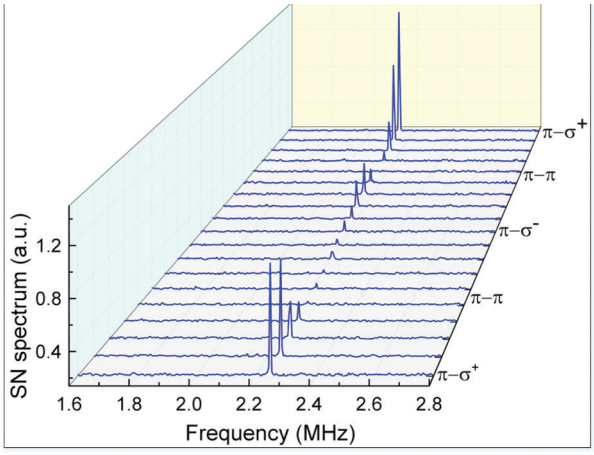


Figure 6. Spin correlation signal from cold atoms driven by a pair of Raman beams. The spin correlation spectrum is plotted against Raman detuning and polarization of the two Raman beams

Here the correlation signal has been measured as a function of Raman detuning as well as polarization of the Raman laser beams. This result can be used to implement a

quantum switch, where changing the polarization of Raman (control) beams can non-perturbatively control the spin correlation. When this experiment was repeated with room temperature atoms the polarization dependence cannot be observed, thus highlighting the need and applicability of ultra- cold atoms in this quantum switching.

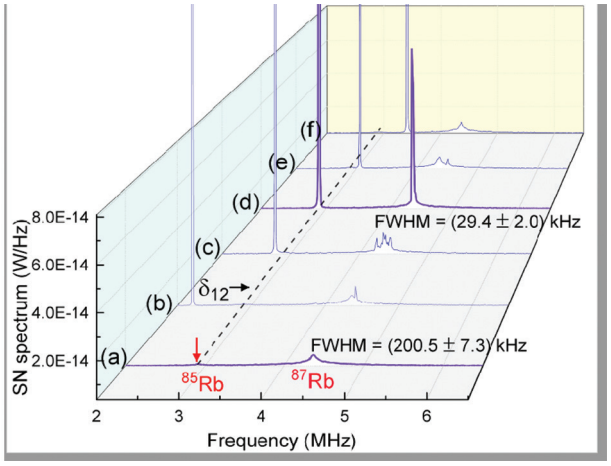


Figure 7. Direct detection of spin exchange collisions via spin correlation spectroscopy in Rubidium atoms.
[Maheswar Swar, Dibyendu Roy, Subhajit Bhar, Sanjukta Roy and Saptarishi Chaudhuri]

Intense Light - Matter Interactions

At weak light levels the optical response of a material scales linearly with respect to the incident light intensity. However, when the intensity of the incoming radiation is sufficiently strong, the response becomes nonlinear. The study of the interaction of strong light fields with matter is called Nonlinear Optics. During the past year, members of Reji Philip's Ultrafast and Nonlinear Optics lab at RRI and collaborators studied nonlinear absorption of various materials for applications as optical limiters; generated laser induced plasmas from Ag nanoparticles with enhanced X-ray generation capabilities and fabricated durable superhydrophilic surfaces by laser induced micro and nanoscale pattering of surfaces.

Nonlinear optical (NLO) phenomena in novel materials of the nano and other size domains.

Overview:

Nonlinear optical devices have various technological applications. One of such devices is the optical limiter, which protects sensitive optical detectors and human eyes from potential damage due to accidental exposure to intense laser beams. Optical limiters keep the power transmitted by an optical system well below some specified maximum value, regardless of the magnitude of the input. They maintain a high transmittance at low input powers, and a reduced transmittance at high input powers.

Motivation and current challenges in the field:

A useful optical limiter has to meet stringent design requirements regarding low-intensity transparency, high-intensity opacity, broad wavelength range, large dynamic range and damage threshold, and fast temporal response. It is very difficult to find materials which can meet all these requirements simultaneously. Therefore, the search for newer and better optical limiters is ongoing in many laboratories across the world. The motivation for this study is the quest for developing novel optical power limiting materials, which can protect sensitive detectors and human eyes from harmful laser radiation.

Description of the research work:

During the past year, members of the Ultrafast and Nonlinear Optics (UNO) lab undertook nonlinear absorption measurements in various materials: (i) the nonlinear optical crystals L-histidine tetra fluoroborate [N.L. John et.al., *Spectrochim. Act. A* **226**, 117615 (2020)] and toluidine tartrate [M. George et.al., *J.Photochem.Photobiol. A* **393**, 112413 (2020)], (ii) the organic luminescence material 2,6-bis (4-chlorobenzylidine) cyclohexanone [J. George et.al., *Opt. Mat.* **100**, 109620 (2020)], (iii) nitropyrene adsorbed on silver [U.R. Felscia et.al., *Mat.Chem.Phys.* **243**, 122466 (2020)], (iv) Fe_3C-graphite core-shell nanoparticles [R.Kumar et.al., *Carbon* **153**, 545 (2019)], (v) sol-gel derived $KBiFe_2O_5$ polycrystalline powder [R. Rai et.al., *J.Mat.Sci. Mat.E*, https://doi.org/10.1007/s10854-019-01494-8] and (vi) Ag_9 quantum clusters embedded in TiO_2 nanotubes [K. Sridharan, *Opt.Mat.* **94**, 53 (2019)]. 5 ns laser pulses at 532 nm were used for exciting the samples. Ag_9 quantum clusters were excited by 100 fs, 800 nm pulses as well, for making a comparative study. From these measurements, the effective two-photon absorption coefficients of the materials were calculated. During the past year, seven publications have resulted from this study. Results obtained from this study indicate the potential of these materials for application as efficient optical limiters for the safety of human eyes and sensitive optical detectors from accidental exposure to harmful laser radiation.

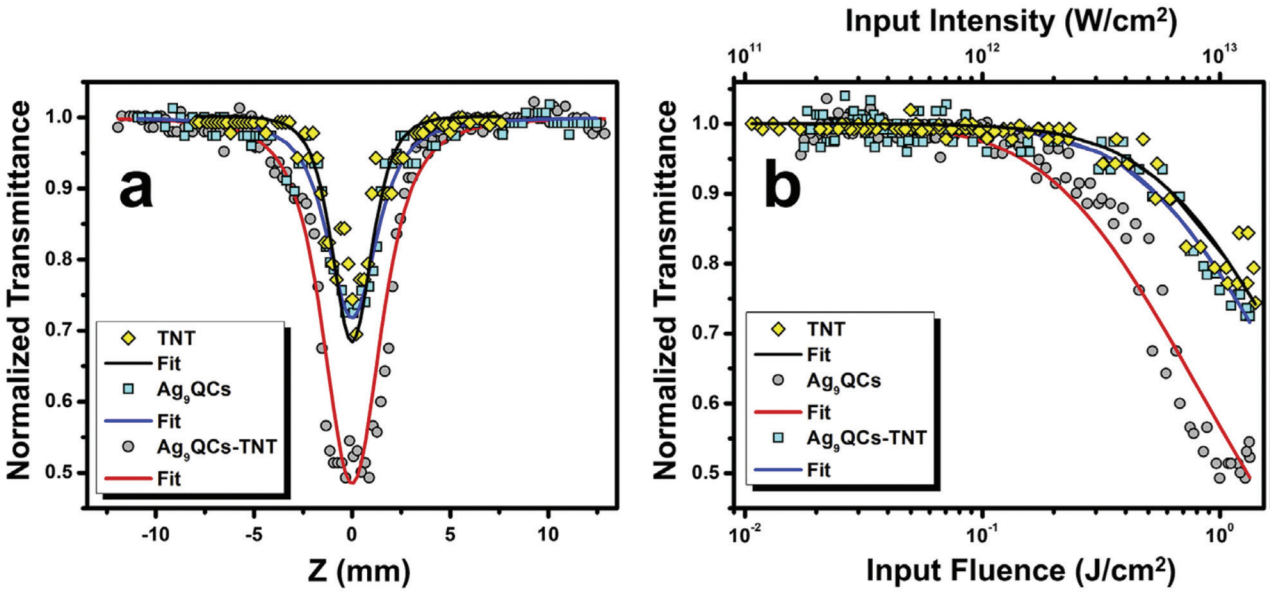


Figure 8. (a) Open aperture Z-scan curves, and (b) normalized transmittance plotted as a function of input fluence and intensity, for TiO_2 nanotubes, Ag_9 quantum clusters, and TiO_2-Ag_9 nanocomposites respectively, using 800 nm, 100 fs laser pulses [from K. Sridharan, P. Sankar and R. Philip, Opt. Mat. 94, 53 (2019)].

[Reji Philip, B. Sahoo (IISc, Bangalore), K.Sridharan (University of Calicut, Calicut), S. Leela (Bharathidasan University, Tiruchirapalli), M. Molli (SSSIHL, Prasanthi Nilayam), D. Sajan (Bishop Moore College, Mavelikara), and B. Mary (Lady Doak College, Madurai). These collaborators supplied the materials which were investigated for the NLO behavior.]

Properties and applications of Laser produced plasmas (LPPs).

Overview:

The nature of the interaction between a powerful laser pulse and a target depends on the laser characteristics (fluence, pulse duration, wavelength, beam quality), target composition, nature of the target surface, and the background gas (pressure and composition). Under the right circumstances a plasma plume will be formed on the target. Laser-produced plasmas have diverse applications including pulsed laser deposition (PLD), nanoparticle generation, high harmonic generation (HHG) and EUV & X-ray production.

Motivation and current challenges in the field:

Plasma X-ray sources produced by ultrashort laser pulses are useful for X-ray lasing and soft X-ray microscopy, and for probing ultrafast real-time physical, chemical and biological dynamics. Research efforts at the UNO lab are currently towards optimizing plasma X-ray sources by choosing the appropriate laser pulses and suitable irradiation targets.

Description of the research work:

Reji Philip and his group members Pranitha Shankar, Jyothis Thomas, H D Shashikala irradiated a thin flowing jet (250 μm) of Ag nanoparticle colloidal suspension by using 150 femtosecond, 800 nm laser pulses to form a plasma which emitted bremsstrahlung X-rays of up to 100 keV energy. The flowing jet ensures long-term stability of the plasma source during continuous laser irradiation. A 30-fold enhancement is observed in the X-ray yield in the nanoparticle suspension, compared to that of the precursor salt solution. This is because of the local field enhancement

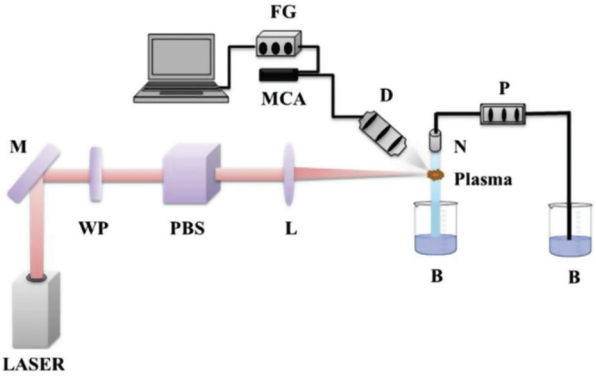


Figure 9. Schematic of the experimental setup for bremsstrahlung X-ray generation. A thin (250 micrometer) jet of colloidal metal nanoparticles is irradiated by using 800 nm, 150 fs laser pulses. Emitted X-rays are detected by a CdTe X-ray detector. M - Mirror, WP - Half-wave plate, PBS – Polarizing beam splitter, L – Lens, B – Beaker, N – thin metal nozzle, P – Pump, D – Detector, FG – Function generator, MCA – Multi-channel analyzer [from P. Sankar et.al., Opt. Mat. **92**, 30 (2019)].

(LFE) associated with the localized surface plasmon resonance (LSPR) in Ag nanoparticles. Multiphoton ionization will be greatly enhanced in the presence of LFE, resulting in the generation of a relatively larger number of free electrons, which become "hot" electrons of high kinetic energy by resonance absorption. Bremsstrahlung in the X-ray regime occurs due to the deceleration of these hot electrons [P.Sankar et.al., Opt. Mat. **92**, 30 (2019)].
[Pranitha Shankar, Jyothis Thomas, H D Shashikala and Reji Philip]

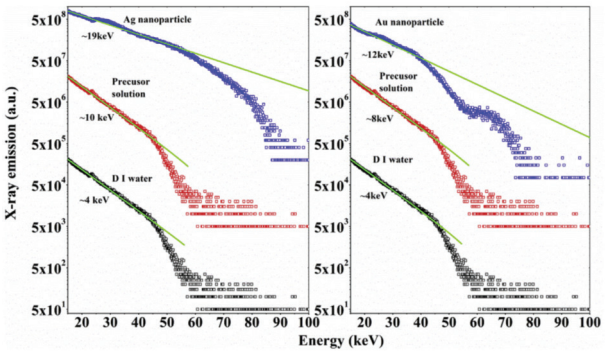


Figure 10. Energy spectrum of bremsstrahlung X-ray emission measured in Ag and Au nanoparticle suspensions and their precursor solutions for a laser pulse intensity of 7.4 x 10^{14} W/cm^2. Total counts measured for the first 9000 laser pulses are shown [from P. Sankar et.al., Opt. Mat. **92**, 30 (2019)].

Surface nanostructuring of solids using laser pulses

Overview:

Laser-induced periodic surface structuring (LIPSS) is a very successful technique for the fabrication of diverse surface patterns on solid surfaces, with micron and sub-micron scale features. LIPSS patterns are formed from the interference between incident laser light and surface scattered electromagnetic waves (SEWs).

Motivation and current challenges in the field:

LIPSS provides a fast and effective way to alter the surface morphology of a material, for tailoring its optical (light absorption and emission), mechanical (e.g., adhesion, wetting) and electrical properties. Nanostructuring of semiconductor materials has applications in nanoelectronics as well. LIPSS is an expanding area because of the ever increasing demand in industry for miniaturized devices for a multitude of applications.

Description of the research work:

Large area (6×6 mm^2) laser micro/nano textured silicon (100) samples using Nd:YAG laser pulses (wavelength = 532nm; pulse width = 7ns) were fabricated and their wetting behaviour was studied. Experiments revealed the formation of laser-induced craters with a nearly flat bottom, with concentric nanoripples appearing along the rim of the irradiated region when higher laser fluences were used. The hierarchical structures consisted of microscale channels and self-organized surface nano-capillaries decorated with randomly distributed silicon nanoparticles. The combination of microchannels and nanocapillaries resulted in a superhydrophilic silicon surface, with the contact angle reduced substantially from about 80^o to nearly 5^o. In contrast to most of the reports given in literature, the superhydrophilicity of the surface remained stable without a shift to hydrophobicity, even after exposure to atmosphere for about three months. Thus, long-lasting and durable superhydrophilic silicon were obtained by using maskless, compact and cost effective nanosecond laser writing, without the need to employ any chemical post-processing. Potential applications of these surfaces include heat exchangers, biosensors, cell adhesives and self-cleaning solar cells. An article based on this study has been prepared and communicated.
[Reji Philip and K.K. Anoop (Dept. Of Physics, CUSAT)]

Quantum Communications, Quantum Optics, Fundamental Tests of Quantum Mechanics and Quantum Information

Quantum Communications

The area of quantum communications is an exciting new area not only for RRI but also for the Indian community. The currently prevalent means of secure communication is through classical cryptography. When the information to be communicated needs to be kept secure for instance in defence, banking and other such strategic sectors, the information is encoded by the sender in what is called a "key" which is then decoded by the receiver by using the key in their possession. The distribution of the key forms the basis of the security and one of the common techniques used is based on the algorithmic hardness of problems for instance the factorization problem. For instance, multiplying two numbers has a lower class of "hardness" in terms of algorithmic complexity than factorization of a number into its two prime factors. Factorization has long been used as the basis of security in public key distribution algorithms like the RSA algorithm. In what is called "Private Key" distribution, one still needs to reply on trusted human carriers. The imminent onset of small quantum registers jeopardizes the security of classical key distribution as

they would be able to run what are called Shor's algorithm which can break the hardness of the factorization problem. What is needed is a "quantum" solution to the problem where the basis of the security are laws of nature and not mathematical hardness of problems or algorithmic complexity. This brings us to "Quantum Key Distribution" or QKD. QKD uses laws of quantum mechanics to ensure "absolute" security of key distribution.

In the area of quantum communications, members of the Quantum Information and Computing lab (QuIC) at RRI are working on several projects which include investigations of different quantum key distribution (QKD) protocols in free space, fibre as well as integrated photonic chips. They are also beginning to work on non-QKD based quantum communication protocols like quantum teleportation, first in free space and then in the fibre domain. All the projects undertaken are geared towards solving one of the most longstanding and cutting edge problems in quantum communication which involves increasing the distance over which this communication happens. While they are laying several test beds towards Long Distance Quantum Communications, one of their main endeavours in that direction involves increasing the distance by using a satellite as a trusted node. In fact, QuIC lab is leading India's first satellite based QKD project in collaboration with the Indian Space Research Organization which opens the way for tremendous possibilities in future. They are also working on integrated photonics based QKD in collaboration with Italian colleagues under the DST-ITPAR programme.

Towards the project on "Quantum Experiments using Satellite Technology (QuEST)", several ground based milestones have been achieved over the past year. This is an ambitious multi-year project to demonstrate free space quantum key distribution over different distance domains in varying environmental conditions. This project is in collaboration with the Indian Space Research Organization (ISRO) and will involve demonstrating quantum key distribution over large distances using a satellite as a trusted node. This is India's first project in satellite based quantum communication and they are extremely excited by its prospects and look forward to reporting on different milestones in the years to come.

Rishab Chatterjee, Sourav Chatterjee, Kaushik Joarder, A. Nagalakshmi, A. Anuradha, Rakshita R.M. and the PI of the project, Urbasi Sinha are currently the people involved in the project with V. Mugundhan from EEG providing them with able technical consultancy. More people are expected to join this project over the course of the next year.

The project started in January 2018 and the first year essentially saw the project being established on a firm footing in the lab with dedicated personnel being hired as well as dedicated equipment and resources being acquired. Sourav Chatterjee, A. Nagalakshmi and A. Anuradha joined the project in 2019. Along with consolidation and mobilisation, they have been extremely productive scientifically. Last year, the B92 protocol was established in the lab with an average key rate of 46 Kbits/second and average QBER of 3.5% over a ~ 2 metre free space distance (to the best of knowledge, these are better than any other reported numbers on this in existing literature). Details of this work on this project can be found on their dedicated website: http://www.rri.res.in/quic/

This year's progress: While an in lab version of the B92 protocol was demonstrated last year, this year the key rates were improved further. One of the major accomplishments in this project this year was coming up with a much needed simulation toolkit, which is able to simulate end to end QKD protocol taking into account practical experimental imperfections. While there are a few commercially available toolkits, none of them seems to contain imperfections and practicalities associated on ground. Their toolkit aims to bridge this very important gap and this work has resulted in a publication.

arXiv reference: qkdSim: An experimenter's simulation toolkit for QKD with imperfections, and its performance analysis with a demonstration of the B92 protocol using heralded photon, Rishab Chatterjee, Kaushik Joarder, Sourav Chatterjee, Barry C Sanders, Urbasi Sinha, arXiv: 1912.10061

Technical abstract:

Quantum Key Distribution (QKD) is one of the most important aspects of quantum cryptography. Using laws of quantum mechanics as the basis for security, the key distribution process is made information theoretically secure in QKD. With the advancement and commercialization of QKD, an end-to-end QKD simulation software is required that can include experimental imperfections. Software of this kind will ensure that resources are invested only after prior performance analysis, and is faithful to experimental capacities and limitations. During 2019-20, Urbasi Sinha, her group members Rishab Chatterjee, Kaushik Joarder, Sourav Chatterjee and collaborator Barry Sanders have introduced a QKD simulation toolkit qkdSim, which is ultimately aimed at being developed into such a software package that can precisely model and analyse any generic QKD protocol. The design, implementation and testing of a prototype of qkdSim that can accurately simulate their own experimental demonstration of the B92 protocol was carried out. The simulation results showed good match with experiment; a representative key rate and QBER from experiment is 51 ± 0.5 Kbits/sec and $4.79\% \pm 0.01\%$

respectively, wherein the simulation yields 52.8±30.36 Kbits/sec and 4.79%±0.01% respectively. In this work, a novel implementation of the B92 protocol has been devised, using heralded single photons, avoiding some of the usual security loopholes. Innovative data optimisation strategies for the same have been developed, details of which can be found in the above reference. The key rate in this study is higher than other known implementations of the B92 protocol using single photons.

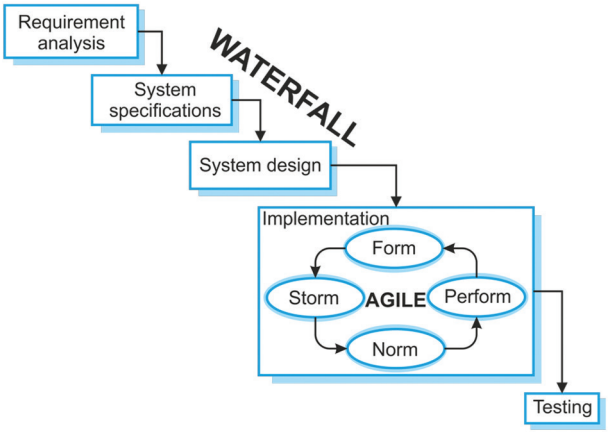


Figure 11. A schematic of the hybrid process model used to build qkdSim. The outline of the simulator has been developed on the Waterfall model, while its implementation-based intricacies have been modelled using the Agile design procedures. [arXiv: 1912.10061]

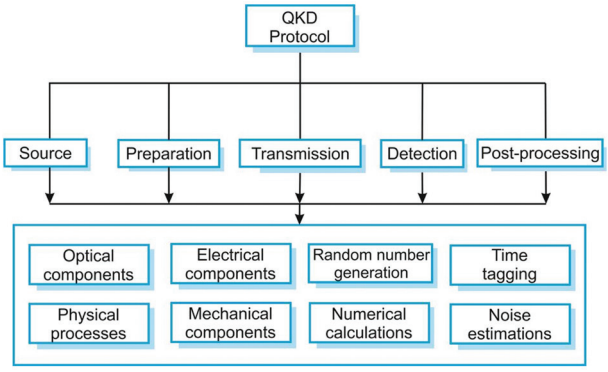


Figure 12. Architecture of the simulation toolkit [arXiv: 1912.10061]

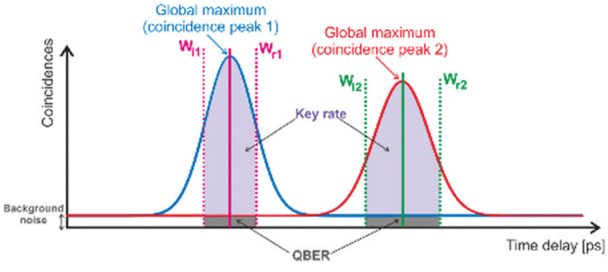


Figure 13. A simplified schematic of the output of two independent coincidence detections: Alice and Bob's R basis (coincidence peak 1 in blue) versus Alice and Bob's D basis (coincidence peak 2 in red). The background noise zone indicated below the flat portions of the blue and red curve represents the unwanted coincident detection from stray light sources, uncorrelated signal and idler photons, leaked pump photons, and dark noise of the photodetector. The symbols $W_{l1}(2)$ and $W_{r1}(2)$ represents the left and right markers of the time window around the maximal coincidence point for coincidence peak – 1(2). The total coincidences within the chosen window around the central maximum from both curves contribute to the error-free "key rate" (or signal – marked in purple); while those within the background noise zone contribute to the "QBER" (or noise – marked in grey). Note that in reality, the coincidence curves are not typically smooth functions and contain a lot of kinks (local optimal points) around a central global maximum. [arXiv: 1912.10061]. Quantum Communications

Crystal length (mm)	Time of the day	Optimization strategy A					
		From experiment			From simulation		
		key rate (kHz)	QBER (%)	asym-metry	key rate (kHz)	QBER (%)	asym-metry
20	Day	47.6 ±0.6	4.79 ±0.01	49.82 ±0.01	53.1 ±0.3	4.79 ±0.01	50.1 ±0.06
	Night	51.0 ±0.5	4.79 ±0.01	50.15 ±0.02	52.8 ±0.4	4.79 ±0.01	50.1 ±0.05
30	Day	33 ±2	4.78 ±0.01	50.07 ±0.02	64 ±1	4.78 ±0.01	50.05 ±0.08
	Night	36 ±3	4.78 ±0.01	50.08 ±0.02	60 ±2	4.79 ±0.01	50.01 ±0.11

Crystal length (mm)	Time of the day	Optimization strategy B					
		From experiment			From simulation		
		key rate (kHz)	QBER (%)	asym-metry	key rate (kHz)	QBER (%)	asym-metry
20	Day	47.8 ±0.6	4.79 ±0.01	50.2 ±0.3	60.0 ±0.2	4.79 ±0.01	57.0 ±0.2
	Night	53.8 ±0.4	4.79 ±0.01	53.7 ±0.3	59.8 ±0.2	4.79 ±0.01	57.0 ±0.2
30	Day	36 ±2	4.79 ±0.01	54.0 ±0.3	71 ±1	4.79 ±0.01	57.1 ±0.3
	Night	38 ±3	4.78 ±0.01	54.1 ±0.4	66 ±2	4.79 ±0.01	57.1 ±0.3

Figure 14. LHS: Optimised results of average key rate, QBER and asymmetry (i.e. key symmetry), obtained using strategy A, from the experiment and the simulations. Note that an asymmetry value of "x" implies that the ratio of "0" bits to "1 bits" in the key is x: (100-x). RHS: Optimised results of average key rate, QBER and asymmetry, obtained using strategy B, from the experiment and the simulation.

This work, along with its attendant analysis, experimental results and algorithms is a major milestone in the ongoing QuEST project with ISRO. Along with these results, they have also been able to demonstrate entanglement based quantum key distribution in the lab. A dedicated entangled photon source for the purpose (with an extremely high Concurrence of 0.99) has been developed and a first version of the BBM92 entanglement based QKD protocol has been demonstrated in the lab. A report on the details of this demonstration will be shared in next annual report after further optimisation of the key rates and QBER.

With this, the QuIC lab is reportedly the first lab in India to have working experimental demonstrations of both

"Prepare and Measure" type QKD as well as entanglement based QKD. Future efforts will be towards exploring the same in open air conditions.
[Rishab Chatterjee, Kaushik Joarder, Sourav Chatterjee, Barry C Sanders (University of Calgary, Cananda) and Urbasi Sinha]

Quantum Optics

A major accomplishment in the QuIC lab in the domain of Quantum Optics during the past year has been a review article on the topic of single photon sources and their uses in quantum information processing.

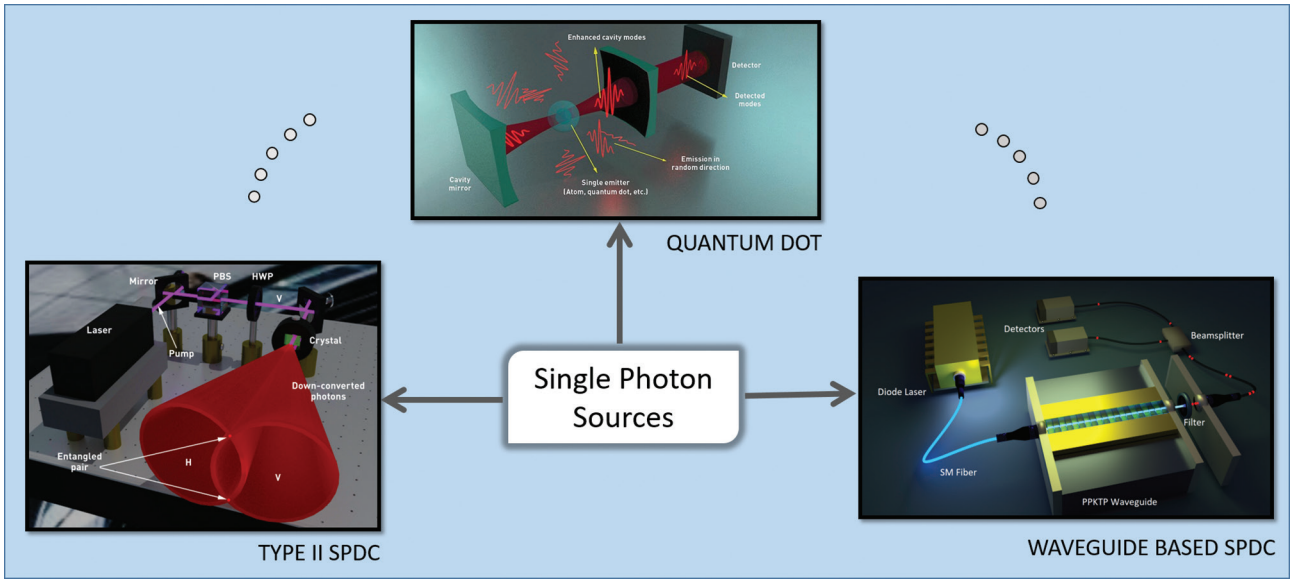


Figure 15. Artist's visualization of the spectrum of SPS architectures with three of the most popular ones being highlighted. [U. Sinha et al., Optics and Photonics News 30 (9), 32 (2019).]

Source	P/D	Emission Range	Band-width	Operating Temperature	Emission Direction	Efficiency	Max. Brightness	Best $g^{(2)}$	Entanglement Fidelity	HOM Visibility	Application†
SPDC	P	600-1700 nm	nm	0-200 °C	Narrow	0.84	2.01 MHz[a]	0.004	0.9959	0.99	QM, QI QF, QC
Atoms & Ions	P,D[b]	Transition Lines	10 MHz	Room Temp, mK (in cavity)	Random, Narrow[c]	0.88	55 kHz	0.0003	0.93	0.93[d]	QF
Quantum Dots	D	IR, Telecom	nm	Room Temp. , Cryogenic[e]	Random, Narrow	0.97	28.3 MHz	0.000075	0.978	0.9956	QC, QF
NV Centre	D	600-800 nm	1-100 nm[f]	300-500 K	Random	0.35	850 kHz[g]	0.07	---[h]	0.66	QC, QN
4 Wave Mixing	P	600-1550 nm	10 nm	Room Temp.	Narrow[b]	0.26	855 kHz	0.007	0.997	0.97	IP

Figure 16. Comparison of properties and yield of various types of single photon sources. All the parameters mentioned above for a given source type do not necessarily belong to the same study. Some properties like high brightness and maximum anti-bunching may not be achievable simultaneously. a)The highest observed spectral efficiency is 0.41 MHz/mW/nm but here thye have reported the highest raw counts or coincidences b) Deterministic in a cavity, but probabilistic in general. c) Cavity makes the emission direction narrow. d) The visibility is 0.93 after background correction. The raw value is 62% e) Cryogenic for Colloidal Quantum Dots and Room Temperature for Epitaxial Quantum Dots f) It's about 1 nm for the ZPL and 100 nm for the broadband emission g) Count rates of 35 MHz have been achieved with NV centre but they have $g^{(2)} \gg 0.2$ (850 KHz brightness gives $0.08\ g^{(2)}$) h) While entanglement between NV centre with another NV centre or photon has been demonstrated, generation of entangled pair from NV centre is currently at the stage of theoretical proposal. †QM=Quantum Metrology, QI= Quantum Information, QF = Quantum Foundations, QC = Quantum Communication, QN = Quantum Network, Integrated Photonics P/D: Probabilistic source/Deterministic source Efficiency: For SPDC and FWM, heralding efficiency is considered whereas for atoms and ion sources the efficiency with which photons are generated in cavity is mentioned. Usually the collection efficiency for non-cavity based sources would make the overall efficiency as low as 0.0001. For Quantum Dots and NV Centre the Quantum Efficiency was reported. Entanglement Fidelity: It is a measure of overlap of the obtained state with the expected entangled state. Maximum Brightness: For SPDC, they report the raw heralded coincidence counts that are detected. For atom/ion source the fluorescence observed was reported. Further, chip based waveguide sources have been demonstrated to have high count rates of 2.1 MHz with $g^{(2)}$ of 0.023. Furthermore, with single molecules, detection rates of 310 KHz have been achieved. [U. Sinha et al., Optics and Photonics News 30]

This lab is one of the first labs in India to manufacture and apply single and entangled photons to varied problems in experimental quantum information processing, quantum computing as well as quantum communications. This year, Urbasi Sinha received an invitation to write a feature article reviewing the state of the art in single photon sources by the well-known broad spectrum optics magazine *Optics and Photonics News* (OPN) published by the Optical Society of America. She included all her current experimental PhD students thereby enabling them to gain invaluable experience in working as a team. This article was published in Optics and Photonics News Vol. 30, Issue 9, pp. 32-39 (2019).

Fundamental Tests of Quantum Mechanics

While the QuIC lab focuses on cutting edge experiments which have both scientific as well as technological implications, their basic principle remains exploitation and exploration of laws of quantum mechanics. One of the thrust areas always has been towards investigation of various principles of quantum mechanics with precision experiments that would give realistic bounds on their experimental validity which in turn would help in devising realistic applications.

One of the principles which they have been testing over the last few years is called the Superposition principle. Quantum Mechanics allows states to be in a superposition of more than one possibility which makes it very different from classical systems where a state always has a definite value. This is what gives rise to the exponential power of quantum computing among many other applications.

In 2014 and 2015, through theory work published in *Physical Review Letters* as well as *Scientific Reports*, they were able to prove the existence of a correction term to the commonly naïve application of the Superposition Principle in slit based interference experiments. Last year, the first experimental measure of this correction term in the classical (microwave domain) was published.

Journal reference*: Measuring the Deviation from the Superposition Principle in Interference Experiments,* G.Rengaraj, U.Prathwiraj, S.N.Sahoo, R.Somashekhar and U.Sinha, *New Journal of Physics,* **20** 063049, 2018.

This year, Urbasi Sinha was invited to write an article on this entire body of work for the prestigious *Scientific American. Quantum Slits open New Doors,* U.Sinha, *Scientific American* (invited article), January 2020 issue

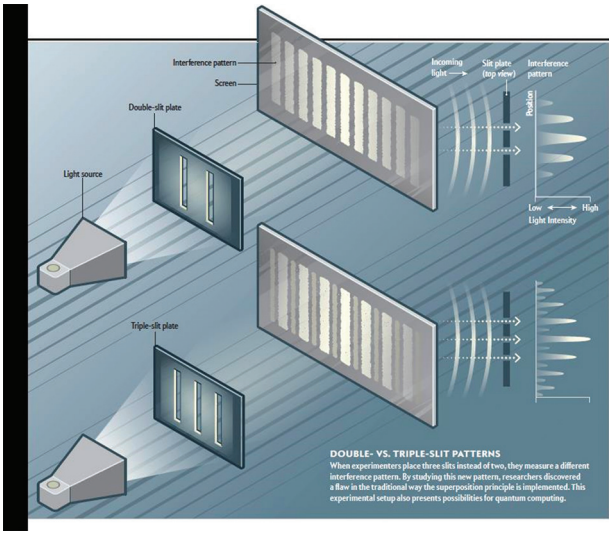


Figure 17. *Illustration from Quantum Slits open New Doors,* U.Sinha, *Scientific American* (invited article), January 2020 issue [Illustration courtesy: Nick Bockelman]

Quantum Information

The first main result from the QuIC lab this year in the domain of quantum information has been in the realm of higher dimensional quantum information processing.

The quantum information and computation community is collectively working towards systems with large number of qubits in coherent superposition. As the exponential advantage of quantum computers goes like 2n where "n" is the number of qubits, more the number of qubits, more the speed up. However, it becomes increasingly difficult to increase n beyond a point due to onset of Decoherence. What could be an alternative approach? Change the base! Instead of two dimensional qubits, one could conceive of using higher dimensional qudits where the "2" is replaced by 3,4,5 and so on. Then, for a smaller "n", one could envisage similar speed up.

Members of QuIC lab are exploring a qudit architecture based on spatial degree of freedom of a single photon. This year, Urbasi Sinha along with collaborators C . Jebarathinam and D. Home have established a novel measure for quantifying entanglement in higher dimensions. While there are well known quantifiers for entanglement in bipartite qubit systems, as the dimensionality of the system increases, it becomes difficult to define a unique quantifier for entanglement. One needs to extract measures of entanglement after state reconstruction using Quantum State Tomography. The number of measurements involved scales exponentially as the dimensionality of the system increases, making this extremely cumbersome. In recent work, they have come up with a novel scheme whereby they have been able to find analytic relations between statistical correlation measures (in this case the well-known

Pearson Correlation Coefficient) and known measures of entanglement (in this case Negativity as a measure of Entanglement). This work was published in Physical Review A.

Technical abstract:

A scheme for characterizing entanglement using the statistical measure of correlation given by the Pearson correlation coefficient (PCC) was recently suggested that has remained unexplored beyond the qubit case. Towards the application of this scheme for the high-dimensional states, a key step has been taken in a very recent work by experimentally determining PCC and analytically relating it to Negativity for quantifying entanglement of the empirically produced bipartite pure state of spatially correlated photonic qutrits. Motivated by this work, Urbasi Sinha and collaborators C Jebarathinam and D Home have undertaken a comprehensive study of the efficacy of such an entanglement characterizing scheme for a range of bipartite qutrit states by considering suitable combinations of PCCs based on a limited number of measurements. For this purpose, they investigated the issue of necessary and sufficient certification together with quantification of entanglement for the two-qutrit states comprising maximally entangled state mixed with white noise and colored noise in two different forms, respectively. Further, by considering these classes of states for d = 4 and 5, extension of this PCC-based approach for higher dimensions was discussed. Journal reference: Pearson Correlation Coefficient as a measure for Certifying and Quantifying High Dimensional Entanglement, C.Jebarathinam, D.Home, U.Sinha, Physical Review A 101, 022112, 2020.
[C Jebarathinam(S. N. Bose National Centre for Basic Sciences, Kolkata), D Home (Bose Institute, Kolkata) and U Sinha]

The second main accomplishment in this domain has also been in the realm of entanglement measures but in bipartite qubit systems.

This work concerns interesting studies on static properties of entanglement which involve comparison between different measures of entanglement and commenting on their equivalence vis-à-vis deviation from the maximally entangled state. Given a non-maximally entangled state, an operationally significant question is to quantitatively assess as to what extent the state is away from the maximally entangled state, which is of importance in evaluating the efficacy of the state for its various uses as a resource. It is this question which is examined in this work for two-qubit pure entangled states in terms of different entanglement measures such as negativity (N), logarithmic negativity (LN), and entanglement of formation (EOF). Although these entanglement measures are defined differently, to what extent they differ in quantitatively addressing the earlier mentioned question has remained uninvestigated. The theoretical estimate in work undertaken by Urbasi Sinha her PhD student Ashutosh Singh and collaborators Ijaz ahmed and Dipankar Home has shown that an appropriately defined parameter characterizing the fractional deviation of any given entangled state from the maximally entangled state in terms of N is quite different from that computed in terms of EOF, with their values differing up to ~15% for states further away from the maximally entangled state. Similarly, the values of such fractional deviation parameters estimated using the entanglement measures LN and EOF also strikingly differ among themselves, with the maximum value of this difference being around 23%. They complemented this analysis by illustration of these differences in terms of empirical results obtained from a suitably planned experimental study. Thus, such an appreciable amount of quantitative non-equivalence between the entanglement measures in addressing the experimentally relevant question considered in the present work highlights the requirement of an appropriate quantifier for such intent. Through this work they indicate directions of study that can be explored towards finding such a quantifier. This work has been published in *Journal of Optical Society of America B*.

Journal reference: *Revisiting comparison between entanglement measures for two-qubit pure states*, A.Singh, I.Ahmed, D.Home, U.Sinha, *Journal of Optical Society of America B*, **37(1)**, 157-166, 2020.

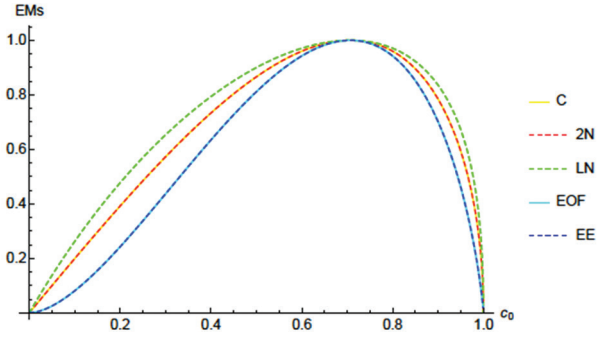


Figure 18. A comparison of different entanglement measures with respect to the state parameter c0 for two-qubit pure states. Here, C, N, LN, EOF and EE denote Concurrence, Negativity, Logarithmic Negativity, Entanglement of Formation and Entanglement Entropy respectively. [*Journal of Optical Society of America B*, **37(1)**, 157-166, 2020]

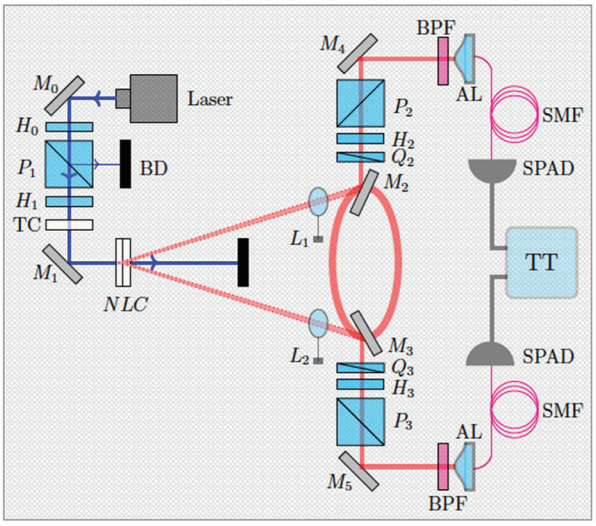


Figure 19. Schematic of the experimental apparatus (not to scale) for preparation of SPDC based Type-I polarisation entangled photon source using two-crystal geometry and characterisation using quantum state tomography. Different symbols have the following meaning: P , polarising beam splitter; Q, quarter wave plate; H, half wave plate; NLC, non- linear crystal; TC, temporal compensator; L, plano-convex lens; M, mirror; BPF, bandpass filter; AL, aspheric lens; SMF, single mode fiber; SPAD, single photon avalanche diode; TT, time tagger unit or coincidence module. [*Journal of Optical Society of America B*, **37(1)**, 157-166, 2020]

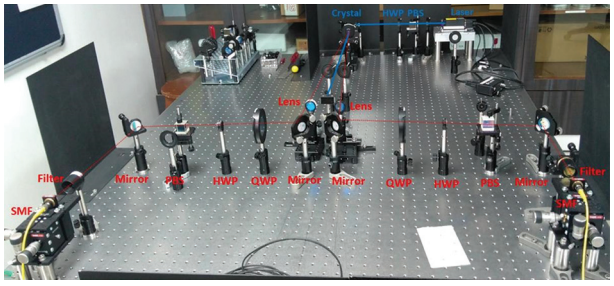


Figure 20. Picture of the entangled photon source in the QuIC lab used in this experiment [Fidelity > 97%]

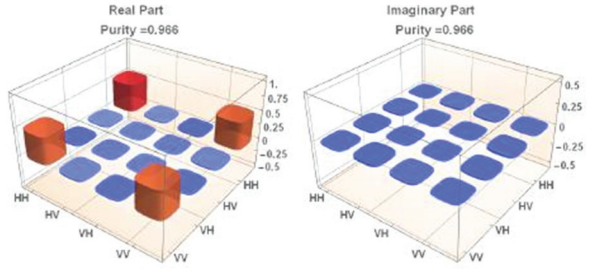


Figure 21. Representative 3D plot of the experimentally reconstructed density matrix for a state with Purity P= 0.966 and 2N = 0.964 (N is the Negativity) [*Journal of Optical Society of America B*, **37(1)**, 157-166, 2020].
[A.Singh, I.Ahmed(IISER, Mohali), D.Home(Bose Institute, Kolkata), and U.Sinha]

The third main accomplishment last year was in the domain of manipulation of entanglement dynamics.

Entanglement is a quantum correlation which serves as a resource in several quantum information, computation and communication protocols. This work concerns preservation of entanglement for its effective use as a resource for applications in quantum communication and quantum computation. Due to interaction with environment, entanglement can get degraded and even disappear within a finite time. In this context, Urbasi Sinha's recent work with her student Ashutosh Singh [arXiv:2001.07604] is of considerable significance because a novel procedure for controlling the degradation of entanglement towards preserving it has been proposed for higher dimensional systems. This along with the previous work is a research direction Urbasi Sinha has been pursuing towards an understanding of both static as well as dynamic properties of entanglement.

The unavoidable and irreversible interaction between an entangled quantum system and its environment causes decoherence of the individual qubits as well as degradation of the entanglement between them. Entanglement Sudden Death (ESD) is the phenomenon wherein disentanglement happens in finite time even when individual qubits decohere only asymptotically in time due to noise. Prolonging the entanglement is essential for the practical realization of entanglement-based quantum information and computation protocols. For this purpose, the local NOT operation in the computational basis on one or both qubits has been proposed in a previous work for all photonic implementation.

This year, they have extended their understanding of Entanglement Sudden Death manipulation to higher dimensional systems and found sets of operations by which ESD can hastened, delayed or avoided even in higher dimensions. This work uploaded on the arXiv is currently under review:
arXiv reference: *Entanglement protection in higher dimensions*, A. Singh and U.Sinha, *arXiv*: 2001.07604
[Ashutosh Singh and Urbasi Sinha]

Quantum Computing

QuIC lab is approaching an exciting new alternative and unconventional approach in the realm of quantum computing. In photonic quantum computing, it is common to use the polarisation degree of freedom of the photon as the basis for the quantum bit. However, this restricts us to 2-dimensional systems. In order to make use of the increased dimensionality of the Hilbert space, as offered by higher dimensional systems (qudits), Urbasi Sinha her

PhD student Simanraj Sadhana and collaborator Barry Sanders have established a novel experimental platform in the lab, which is based on the spatial degree of freedom of the single photon. They call their architecture "spatial bin qudits".

In this context, they have established the first steps towards using spatial bin systems in a new approach to linear optics based quantum computing.

Diffraction-based interferometry is cast in the framework of post-selected unitary description towards enabling it as a platform for quantum information processing. They expressed slit-diffraction as an infinite-dimensional transformation and truncated it to a finite-dimensional transfer matrix by post-selecting modes. Using such a framework with classical fields, a customized double-slit setup is effectively a lossy beam splitter in a post-selected sense. Diffraction optics provides a robust alternative to conventional multi-beam interferometry with scope for miniaturization, and also has applications in matter wave interferometry. In this work, the classical treatment sets the stage for quantization of fields and implementing higher dimensional quantum information processing like that done with other platforms such as orbital angular momentum. This work is published as under:

Journal reference: *Double slit interferometry as a lossy beam splitter*, S.Sadana, B.C.Sanders and U.Sinha, *New Journal of Physics* 21 113022, 2019.

In this context, Urbasi Sinha was invited to wirte an article in the *Scientific American* which featured an illustration, included below:

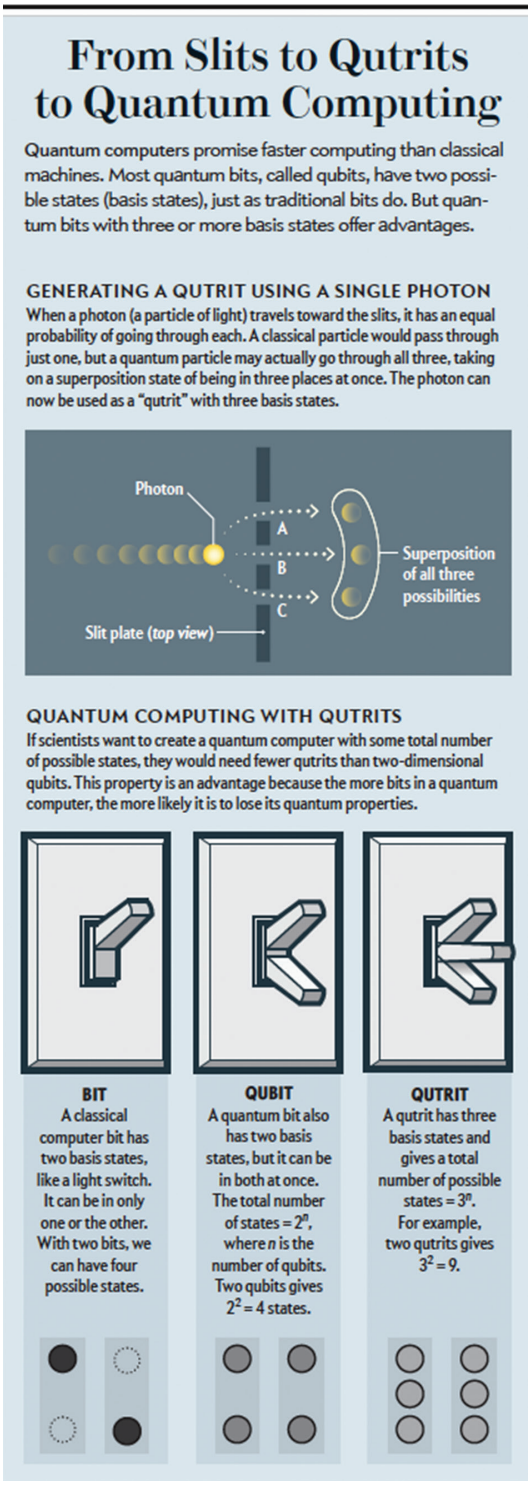


Figure 22. *Illustration from Quantum Slits open New Doors*, U.Sinha, *Scientific American* (invited article), January 2020 issue [Illustration courtesy: Nick Bockelman]

[Simanraj Sadhana, Barry Sanders (University of Calgary, Canada) and Urbasi Sinha]

Research: Knowledge Creation

Soft Condensed Matter

Soft Condensed Matter

Overview

Soft matter, as the name implies, encompasses materials that are easily deformed by thermal fluctuations and external forces. Some common examples of soft matter that we use in our day-to-day life include lotions, creams, milk and paint. The building blocks of these materials are macromolecules with typical size ranging anywhere from few nanometers to few micrometers and are held together by weak inter macromolecular forces and exhibit complex structures and phase behavior. The SCM group at RRI actively studies colloids, complex fluids, liquid crystals, nanocomposites, polyelectrolytes, self-assembled systems, polymers and biological materials. A fundamental understanding of the structure-property correlations, phase behavior of these systems, and response to external stimuli form a major part of the experimental research activities in the SCM group. Theoretical work carried out by the group broadly concerns developing phenomenological theories of elasticity and topological defects in soft matter.

Focus 2019-20

Liquid Crystals

As the name implies, liquid crystals (LCs) is a state of matter that has properties intermediate between those of conventional liquids and solid crystals. An LC exhibits many of the physical attributes of a liquid, whereas its molecular units exhibit some form of order. LCs can be divided into thermotropic LCs in which transitions into an LC phase occur with change in temperature, and lyotropic LCs that are formed by dissolving surfactants - amphiphilic materials composed of a polar head group and non-polar chain - in a solvent.

Thermotropic LCs are further subdivided into calamitic LCs made of rod-like molecules and discotics composed of disc-like molecules. More recently, a new class of LCs made of bent-core molecules has also been discovered. An attractive feature observed in this type of LC is the interplay between polarity and chirality, which leads to various chiral effects despite the molecules being achiral.

LCs display a variety of phases characterized by the type of molecular ordering, the simplest among them being the nematic phase in which the molecules have no positional order, but they self-align to have long-range orientational order with their long axes roughly parallel, and the smectic A phase in which the molecules are parallel to one another and are arranged in layers with the long axes being perpendicular to the layer plane.

Since their discovery, considerable work has gone into understanding their structure-property relationships, which hold the key for the myriad applications involving LCs. Researchers within the SCM group at RRI have done pioneering work in LCs and that tradition still continues today with research in various aspects of LCs being undertaken. The interesting physical properties resulting from a careful tuning of the molecular shape, concentration, constituents and phase, while expanding the LC knowledge base, serve to open potential avenues for technological applications.

Research focus during 2019-20 was on design and synthesis of novel LC's and studying their physical properties, phase transitions and electro-optic properties of LC's and phenomenological theory of stability in curved surfaces.

Phase transition and electro-optics of liquid crystals

Electric field induced transition in pseudopolar tilted smectic phases exhibited by bent core hockey stick shaped molecules

Liquid crystals are a class of soft materials which are charaterized by the presence of orientational order of the constituent molecules. The orientational order can be easily deformed by externally applied electric field giving rise to various electro optic effects and are being exploited for different liquid crystal devices. Arun Roy and his PhD student Deepshika Malkar along with collaborator Veena Prasad had reported experimental studies on an azo-substituted compound consisting of bent-core hockey-stick-shaped molecules. The experimental results established two pseudopolar tilted smectic phases, which were characterized by an in-plane axial-vector order parameter in addition to tilt order in the smectic layers. Electro-optical measurements in the mesophases indicate that the birefringence of the sample strongly depends on the applied electric field. Interestingly, it was found that upon increasing the applied voltage, birefringence color starts to change beyond a threshold voltage. During the past year they have developed a theoretical model to account for this observation. They found that the change in the birefringence of the sample arises from the field-induced reorientation of the tilt plane of the molecules in the layer above a threshold field. This effect is analogous to the field-induced Freedericksz transition which is quadratic in the applied electric field. These results have been published in Phys Rev. E (2020).

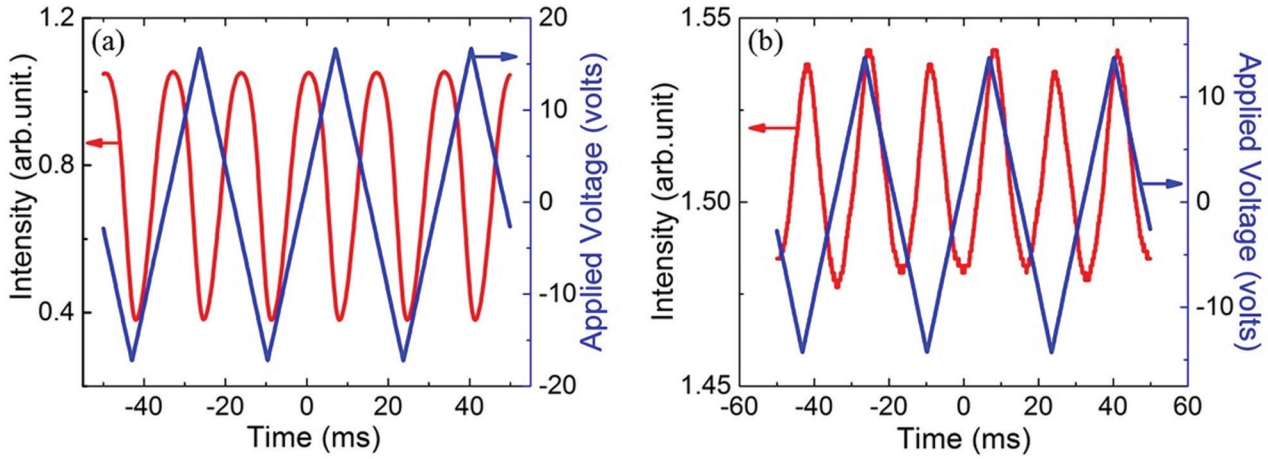


Figure 1. Optical response of a planar-aligned sample of thickness 5 μm under the application of a triangular wave voltage in the (a) SmC A and (b) SmC I phases.

[Deepshika Malkar, Arun Roy and Veena Prasad (CeNS, Bengaluru]

Liquid crystals – phenomenological theory

Stability of topological wall defects on sphere with n-atic order

The remarkable interplay between the curvature of a surface, and frustration of orientational order on it is strikingly demonstrated by the Poincaré-Hopf index theorem. Stated informally, a hairy ball cannot be combed flat without creating at least one hair-whorl; a singular, isolated disclination (vortex), or isolated disclinations with total index (winding number) 2. Vector(1-atic) order disclinations have integer indices, whereas for nematic (2-atic) order they are integer multiples of 1/2. In a region surrounding a disclination (point defect in 2-dimensions), deformations in the orientation-field are large enough to destroy orientational order. Disclinations are topological defects characterised by their index, and have "molten" core regions of finite extent encompassing the disclination points. Topological point defects on orientationally ordered spheres, and on deformable fluid vesicles have been extensively studied, partly motivated by their potential applications in creating super-atoms with directional bonds, and their self-assembly through functionalisation of the "bald-spots" created by topological point defects, thus paving the way for atomic chemistry at micron scales. During the past year, Yashodhan Hatwalne, Arun Roy and RRI PhD student C Saichand along with Jayakumar Alageshan have shown that singular wall defects, topologically unstable "bald lines" in two dimensions, are stabilised near the order-disorder transition on a curved surface such as a sphere. They attribute the stability of such walls to free-energetic considerations, which override those of topological stability. The work has been accepted for publication in Phys. Rev. Research.

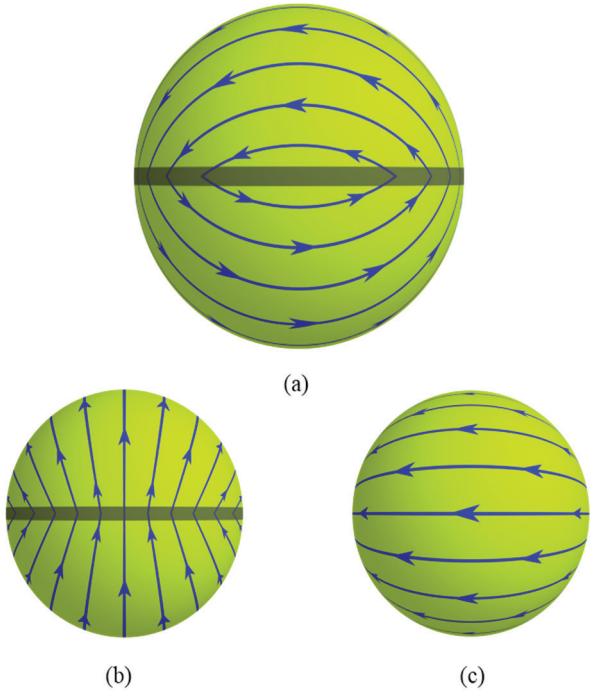


Figure 2. Equatorial wall: (a) Side ($\theta = \pi/2$, $\varphi = \pi/2$ at the centre) view of the index 2, equatorial wall. The directed lines are the streamlines of the vector field. The shaded region represents the disordered core, within which vector order is completely destroyed, and cannot be assigned a direction. The full field, including that shown within the core region, corresponds to a wall with zero core-size. Rounding off the slope singularity of the field at the equator, the wall defect of zero core-size transforms into the antipodal configuration of a pair of index 1 point disclinations. (b) Front view ($\theta = \pi/2$, $\varphi = 0$ at the centre). (c) Top view, showing that the polar regions are free of point disclinations.

[C Saichand, Jaya Kumar Alageshan (IISc, Bangalore), Arun Roy and Yashodhan Hatwalne]

Mechanical properties of soft materials

Force induced adaptations in dense suspensions

Overview:

Dense suspensions formed by adding hard particles in a liquid show interesting non-linear stress response. Under increasing applied shear stress, viscosity of many of these systems increases significantly (known as shear-thickening) and the system can even transform into a jammed solid-like material (shear-jamming). These behaviours are completely reversible and originate from stress induced proliferation of frictional contacts. Gaining a deeper insight into such reversible tuning of mechanical response is crucial for designing smart and adaptive materials for various shock absorbing applications. While steady state viscosity measurements successfully describe the shear-thickening behaviour, they cannot capture any signature of shear-jammed (SJ) state.

Ongoing projects and recent findings:

Shear induced thickening and jamming transition in a well-controlled system of monodisperse spherical colloidal particles (polystyrene) in Polyethylene Glycol (PEG 400) was investigated during the past year by Sayantan Majumdar and his students Subhransu Dhar and Sebanti Chattopadhyay. One major practical challenge to study such problem in the lab comes from the requirement of large quantity of monodisperse particles to form dense suspensions with volume fractions $\phi > 0.5$. The commercially available particles are very expensive and hence only practically feasible for making dilute suspensions.

Optimized large-scale synthesis of monodisperse particles of various sizes has been successfully achieved in the Soft and Adaptive Materials lab to effectively study such problems. They studied the steady state shear-thickening behaviour of dense suspensions formed by dispersing colloidal polystyrene particles in polyethylene glycol and found that for small applied stress values the viscosity of the suspensions as a function of ϕ can be well described by Krieger-Dougherty (KD) relation. However, for higher values of applied stress (much larger than the stress onset for shear thickening), KD relation systematically overestimates the measured viscosity, particularly for higher volume fractions. They attribute this systematic deviation to the weakening of the sample due to flow induced fractures and failures when the sample is in a solid like SJ state. Using Wyart-Cates model, they have proposed a method to predict the SJ onset from the steady state rheology measurements. Their results were further supported by in-situ optical imaging of the sample boundary under shear.

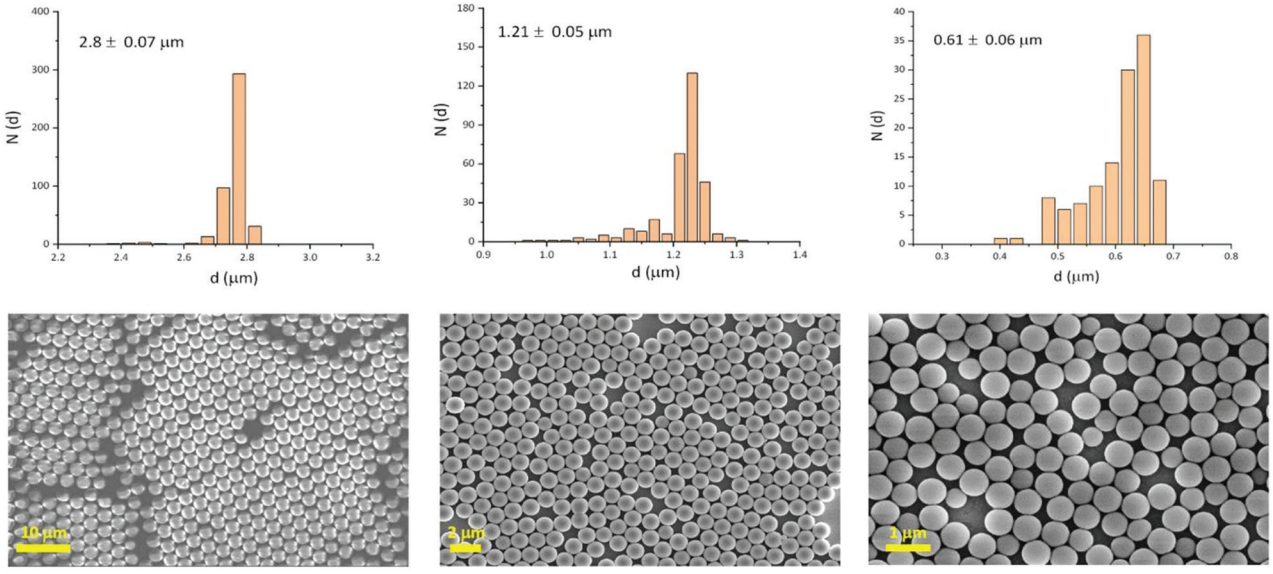


Figure 3. Monodisperse colloidal particles synthesized in large scale in the lab. Distributions of particle diameter obtained from SEM imaging are shown.

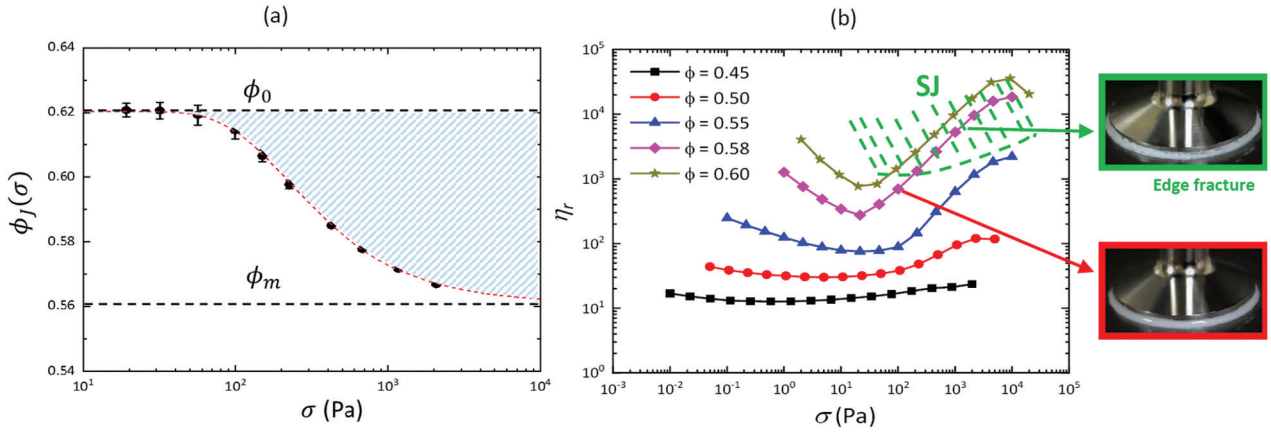


Figure 4. (a) Stress dependent jamming point obtained from asymptotic viscosity divergence obtained for lower σ and ϕ values (away from the jamming point). The dotted line is the fit to Wyart-Cates model. Existence of finite viscosity for the parameters (σ and ϕ) in the shaded region indicates shear-jammed states. (b) Relative viscosity as a function of stress for different packing fractions of particles. The shear jammed phase (SJ) is concluded from (a) and shown in green. Optical image shows edge fracture of the sample for SJ, as indicated. The sample is 1.2 mm polystyrene microspheres in a solution of PEG-400, for both (a) - (c).

[Subhransu Dhar, Sebanti Chattopadhyay and Sayantan Majumdar]

Jamming and yielding in an athermal dense suspension of amorphous particles

Overview:

Many dense suspensions (mainly with particles with attractive interactions) show yielding behaviour. They behave like a solid below a critical stress called the yield stress ($_y$) but transforms into a liquid above $_y$. Understanding yielding in disordered materials is very important in pressure driven transport of materials in large-scale industries as well as from the fundamental points of view. Due to complex microstructures, the mechanical response of many of these materials is highly non-linear even for very small applied strain values. There is no well-defined framework to study yielding in highly non-linear systems.

Ongoing projects and recent findings:

Using oscillatory shear rheology and in situ optical imaging, Sebanti Chattopadhyay and Sayantan Majumdar studied the yielding behaviour of a suspension formed by mixing hydrophilic amorphous granular particles with a hydrophobic solvent. Due to the solvent mediated attractive interactions, the particles formed fractal clusters. The space filling nature of fractals gave rise to a yield stress

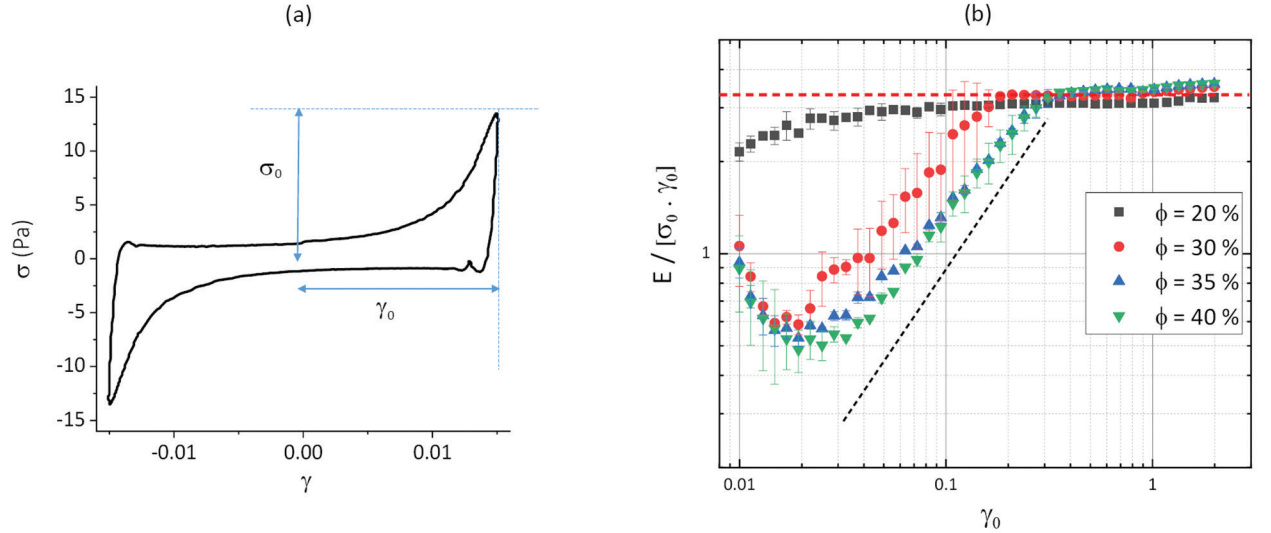


Figure 5. (a) Intra-cycle stress vs strain (Lissajous plot) for a yield stress fluid formed by fractal aggregates of corn-starch particles in paraffin oil obtained from oscillatory strain deformations. (b) Normalized energy dissipation per cycle as a function of applied strain amplitude for different volume fractions (ϕ). Yield stress appears for ϕ > 25%. The dotted line in (b) indicates a power-law slope of 1 in the yielding (fluidization) region. The frequency is fixed at 0.1 Hz in both the cases.

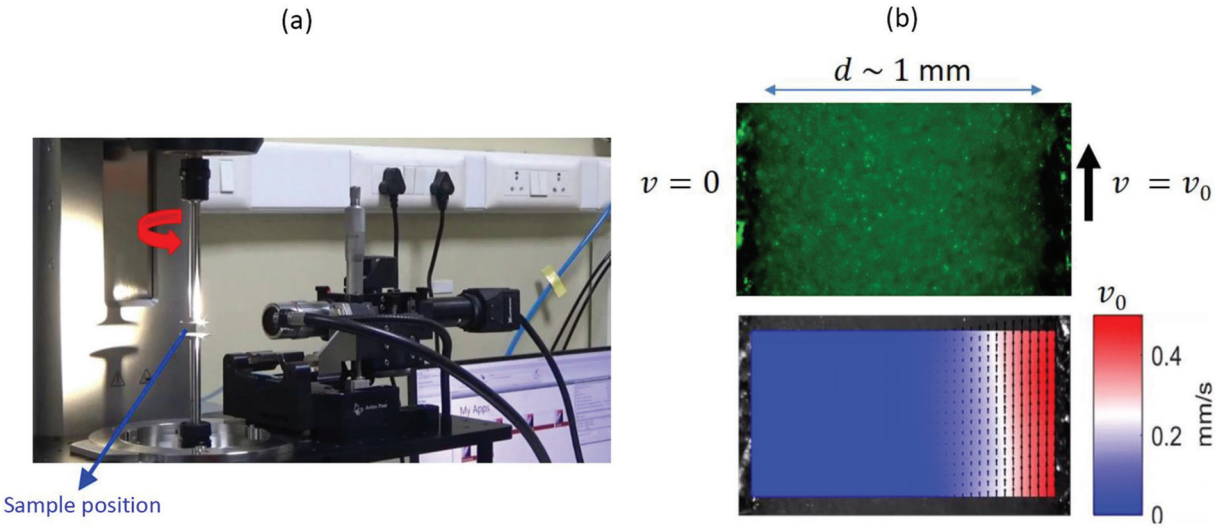


Figure 6. (a) Experimental set-up for rheology and in-situ velocity profile measurements. (b) Typical PIV vectors indicating shear banding in the system under steady-shear (sample: corn starch particles in paraffin oil with $\phi = 20\%$).

for packing fractions ϕ well below their isotropic jamming point ϕ_J. They probed the stress response of the system for a wide range of applied strain amplitudes ($0.0001 < g_0 < 1$) for a fixed frequency. Higher harmonic analysis revealed that the system is highly non-linear almost over the entire strain range. As a result, the linear elastic (G') and viscous (G") moduli did not reliably capture the mechanical response of the system. Upon estimating the energy dissipation for one complete cycle of oscillation from the area of the Lissajous plots (intra-cycle stress vs strain) over the entire range of, they found that the normalized dissipated energy shows a non-monotonic behaviour: it goes through a minimum at an intermediate and saturates at a maximum value for larger values , for all values of ϕ that show yield stress. These results suggest that with increasing applied strain the system first reorganizes to form a more elastic solid-like state that dissipates minimum energy and then gets fluidized at higher strain values when the energy dissipation increases. Near the energy-minima, shear-bands showed interesting time- dynamics.

Current efforts are towards tuning the attractive interactions between the particles to control the non-linearity and intra-cycle energy dissipation in the system. Also, investigations on the role of spatially heterogeneous flow profiles on the non-linearity and the yielding behaviour of the system is underway.
[Sebanti Chattopadhyay and Sayantan Majumdar]

Strain softening and stiffening responses of spider silk fibers probed using Micro-Extension-Rheometer

Overview:

Spider silk possess unique mechanical properties like large extensibility, high tensile strength, super- contractility, light weight etc. It is, in fact, one of the toughest and strongest bio-material known to mankind. Microscopic understanding of mechanical response of such versatile material holds immense possibilities for future technological applications in novel materials design. Despite of broad literatures reporting simple force extension relation of silk fibers, such characterization does not take into account the steady state mechanical behaviour and frequency response for a single silk fiber.

Ongoing projects and recent findings:

Sayantan Majumdar, Pramod Pullarkat and PhD students Sushil Dubey, Sukh Veer along with collaborators Chinmay Joshi, Divya Uma and Hema Somanathan have studied the linear and non-linear viscoelastic properties of dragline silk obtained from social spiders S. sarasinorum using a Micro-Extension-Rheometer that was developed in Pramod Pullarkat's Cell BioPhysics lab at RRI. Unlike continuous extension data, this technique allows for the probing of the viscoelastic response by applying small perturbations about sequentially increasing steady state strain values. In addition, the analysis was extended to obtain the characteristic stress relaxation times and the frequency response of the viscous and elastic moduli. Using these methods, they have shown that in small strain regime (0 - 4%) dragline silk of social spiders shows strain-softening response followed by strain-stiffening response at higher strains. The stress relaxation time, on the other hand, increased monotonically with increasing strain for the entire range. They have also shown that silk stiffens while ageing within the typical lifetime of a web and also suggest a possible mechanism for the observed non-linear response.

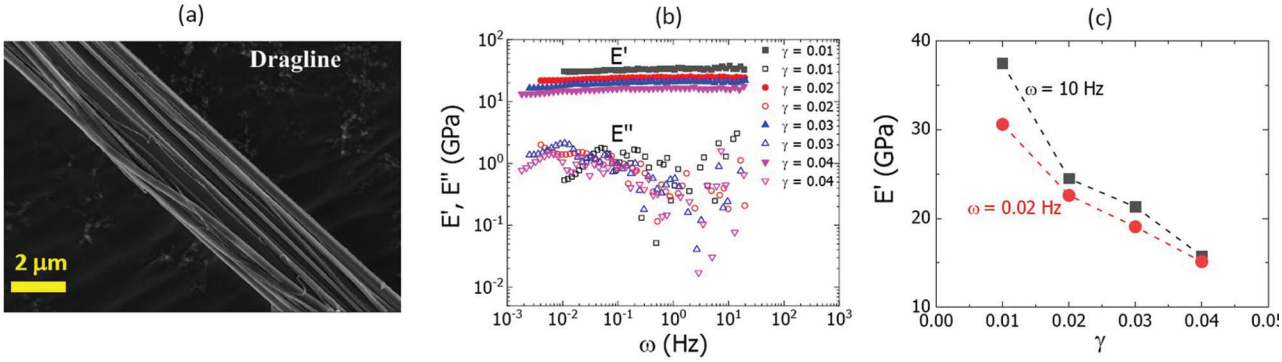


Figure 7. (a) SEM image of a single dragline silk fiber composed of many micro-filaments. (b) Frequency dependent elastic (E') and viscous (E") extensional moduli of a single dragline fiber for different applied strain values obtained from the time domain stress relaxation data. (c) Softening of a fiber with increasing step-strain magnitude shown for two different frequencies.

[Sushil Dubey, Sukh Veer, Sayantan Majumdar, Pramod Pullarkat and collaborators from IISER Thiruvananthapuram: Chinmay Hemant Joshi, Divya Uma, Hema Somanathan]

Structure, dynamics and rheology of non-Newtonian fluid

Influence of particle size on the thermoresponsive and rheological properties of aqueous poly(N-isopropylacrylamide) colloidal suspensions

Ranjini Bandyopadhyay and her PhD students Chandeshwar Mishra and Sanjay Behera synthesized thermoresponsive poly(N-isopropylacrylamide)(PNIPAM) particles of different sizes by varying the concentration of sodium dodecyl sulfate (SDS) in a one-pot method. Characterization of the sizes, size polydispersities, and the thermoresponsivity of the synthesized PNIPAM particles by using dynamic light scattering (DLS) and scanning electron microscopy (SEM) led to the observation that the sizes of these particles decrease with increase in SDS concentration.

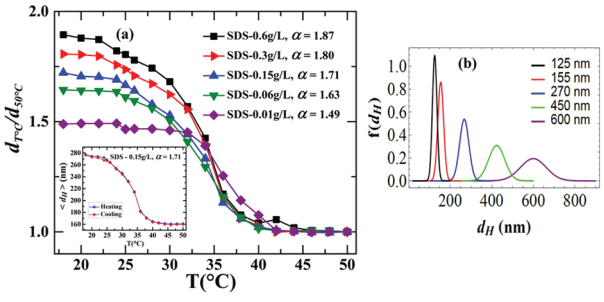


Figure 8. Temperature dependent swelling ratios $d^{o}_{T^{o}C}/d^{o}_{50^{o}C}$ as a function of temperature T of aqueous PNIPAM suspensions for different concentrations of SDS. In the inset, the average hydrodynamic diameter $<d_H>$ of the PNIPAM particles of maximum swelling ratio 1.71 in aqueous suspension is plotted as a function of temperature while heating and cooling. (b) Particle size distributions of PNIPAM particles measured from DLS experiments for different particle sizes synthesized using various SDS concentrations in the one-pot emulsion polymerization method.

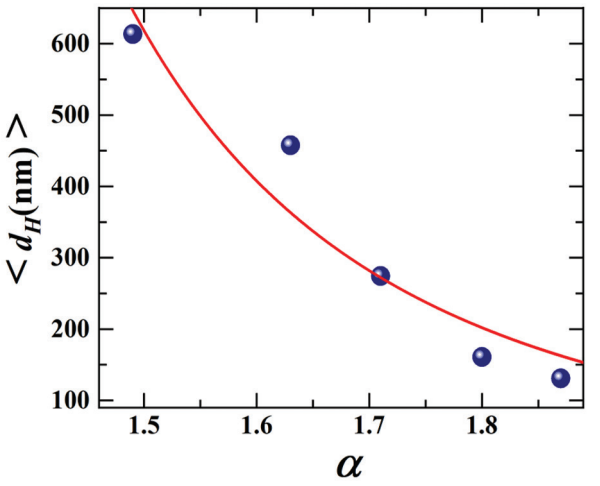


Figure 9. Average hydrodynamic diameter $<d_H>$ of the PNIPAM particles in aqueous suspensions at 20°C as a function of maximum swelling ratio α. The solid line is a fit to their model.

Swelling ratios of PNIPAM particles measured from the thermoresponsive curves were observed to increase with decrease in particle size which they understand by minimizing the Helmholtz free energy of the system with respect to the swelling ratio of the particles. Their study also included rheological measurements to understand the dynamics of these particles in jammed aqueous suspensions. This work has been accepted for publication in the Bulletin of Materials Sciences (a special issue), 2020. [Chandeshwar Mishra, Sanjay Behera and Ranjini Bandyopadhyay]

Physics of Lipid Membranes and Polyelectrolytes

Electrostatic interaction in strong electrolytes: specificity of salts

Electrostatic interaction between two charged surfaces in a dilute electrolyte is well described by the Debye-Huckel theory, according to which the repulsion between the surfaces decreases strongly with increasing ionic strength of the electrolyte. However, V A Raghunathan and his PhD student Anindya Chowdhury had recently observed the re-emergence of electrostatic repulsion at very high ionic strengths, in agreement with some earlier reports. During the past year, they studied the dependence of this effect on the specific ions involved, by using aqueous solutions of chlorine salt of alkali metals, ranging from lithium to cesium. Interestingly, the enhancement of repulsion was observed only in aqueous solutions of LiCl and NaCl, but not in those of KCl and CsCl. They are currently carrying out further experiments to understand this specific ion effect.
[Anindya Chowdhury and V A Raghunathan]

Hydrotropic behaviour of mononucleotides

V A Raghunathan, his student Sreeja Sasidharan and collaborator Himanshu Khandelia have studied the aggregation behaviour of uridine monophosphate (UMP) and its disodium salt (UMPDSS) in water using a variety of experimental techniques as well as computer simulations. They found that UMPDSS behaves like a hydrotrope by forming small aggregates above a critical concentration, which can encapsulate hydrophobic molecules present in the solution while UMP, which is the acid form, does not exhibit such a behaviour. This significant dependence on the counterion species has helped them understand their observation of the vast difference in the interaction of UMP and UMPDSS with neutral lipid membranes.
[Sreeja Sasidharan, Himanshu Khadelia (University of Southern Denmark, Denmark) and V A Raghunathan]

Fluid-fluid coexistence in lipid membranes induced by decanol

Fluid-fluid coexistence in lipid membranes is a topic of much current interest due to its implications for the functioning of cell membranes. In spite of a large number of studies, presently there is no report of fluid-fluid coexistence in single component lipid membranes induced by an additive. V A Raghunathan and his PhD student Buti Suryabrahmam and RRI postdoctoral fellow Ayush Agrawal have recently found that 1-decanol induces fluid-fluid coexistence in dimyris- toylphosphatidylcholine (DMPC) membranes. This behaviour has been established using a variety of experimental techniques. They are currently studying related systems to understand the physical mechanism involved.
[Buti Suryabrahmam, Ayush Agrawal and V A Raghunathan]

Biophysics

Biophysics of Axons

Neuronal cells are the main building blocks of the central and the peripheral nervous systems (CNS & PNS). They first evolved in simple multicellular organisms in order to transmit signals over long distances—like the loose neuronal network in a jelly fish. As evolution progressed, they also organised into complex information storing and processing centres— like the relatively simple head ganglia of C. elegans (~100 neurons) to the much more complex human brain (100 billion neurons). To transmit signals, neuronal cells extend two types of thin tubular processes called dendrites and axons. Typically, dendrites form relatively short highly branched structures, whereas axons can grow to extreme lengths—up to a meter in the human sciatic nerve of the leg and tens of meters in a blue whale.

The extreme lengths to which axons grow poses several challenges to the neuronal cells. The maintenance of these structures and their function require constant back and forth transport of material like neurotransmitters, and material that need to be constantly recycled. Since diffusion is too slow for this (it'll take >100 years for small molecules to diffuse a distance of 1 m), axons rely on molecular motors which can travel at speeds of up to micro-meters per second. Axons also face mechanical challenges as they are subjected to fast stretching during body movements—strain of up to 20% at some joints of mammals. The brain too, being one of the softest of tissues, undergoes shear deformations of the order of 5% in humans during normal activities like jumping, and much more during sudden impacts, like in contact sports. Even in the absence of such external stresses, axons have to maintain a balance of different internal stresses. The plasma membrane, composed of a fluid lipid bilayer, is under tension. A membranous tube under tension is unstable to peristaltic modes via the Rayleigh-Plateau instability, and require additional elements to maintain a uniform tubular form. This is achieved by forming connections with the internal cytoskeleton—an axisymmetric arrangement of different biopolymers and their associated proteins. This cytoskeleton is highly dynamic as the polymers undergo turnover via constant polymerisation-depolymerisation processes and are acted upon by molecular motors which can generate active stresses on the filaments. Thus, the axon is a structure which is maintained under a dynamic

steady state where the different membrane and cytoskeletal forces are balanced against each other. Any changes in this dynamic balance can lead to abnormalities in the axonal form and function. This is particularly significant for neuronal cells as they do not divide unlike other cells in a human body and are rarely replenished when lost. This makes the nervous system particularly susceptible to degeneration causing debilitating conditions. Axons, owing to their extreme lengths, are particularly vulnerable.

The aim of Pramod Pullarkat and his PhD students at the Cell BioPhysics lab is to investigate the mechanical and dynamical properties of the axonal membrane-cytoskeleton complex. For this they have developed an optical fiber based Micro-Extension Rheometer to probe mechanical responses of axons and use optical tweezers to study axonal membrane properties.

The research work carried out at the Cell BioPhysics lab is given below.

Non-linear mechanical responses of axons

Sushil Dubey performed rheological measurements on axons using a modified version of the Micro-Extension Rheometer designed and developed at RRI. He collaborated intensely with biologists Shivani Bodas and Aurnab Ghose from IISER-Pune to perform protein knock- down

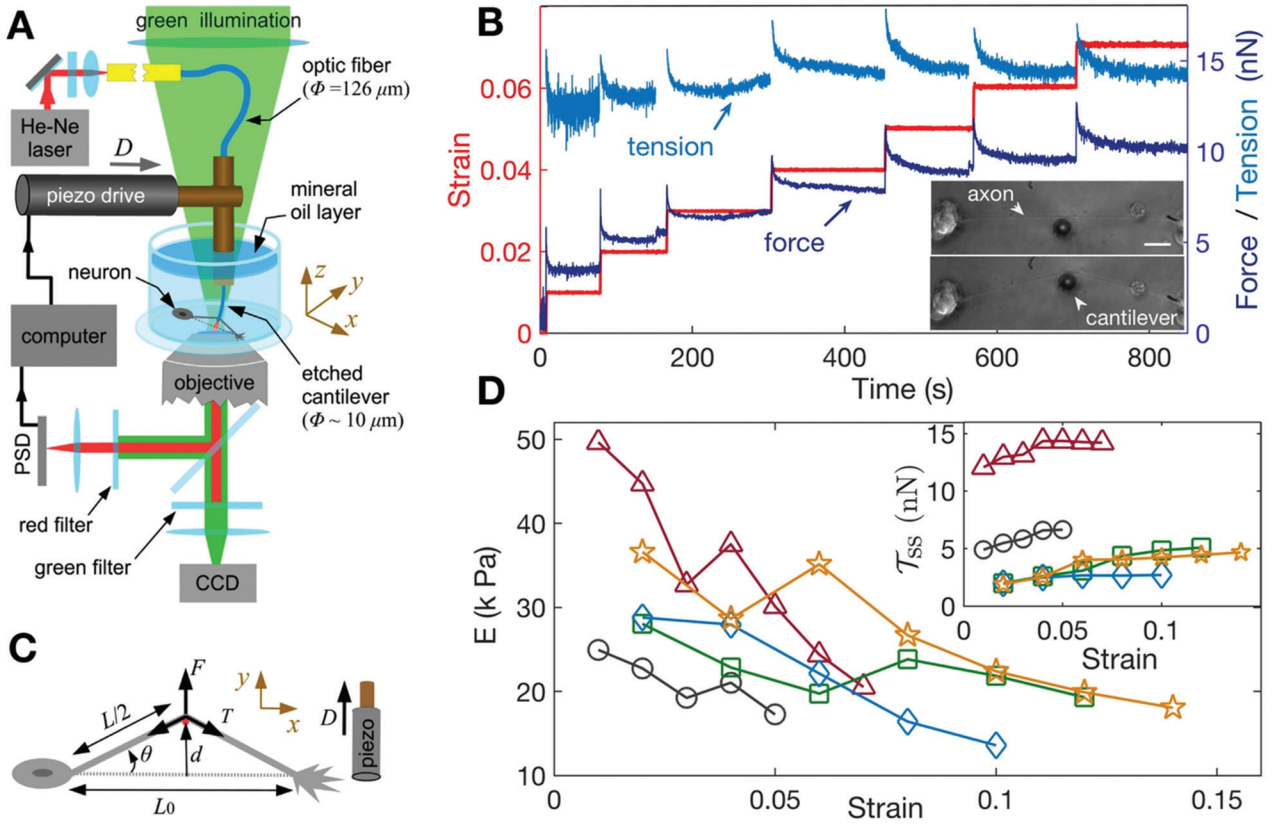


Figure 10. (A) A schematic of the Micro-Extension Rheometer developed at RRI, which uses an etched optical fiber as cantilever and a computer feedback loop to operate in constant strain mode. (B) Plots of the applied strain steps, corresponding measured force and calculated tension. The inset shows images of an axon before and after a strain step. (C) Schematic showing the relation between the measured force and axon tension. (D) Plot of the Young's modulus as a function of strain shows strain softening. The inset shows that the steady state tension saturate with increasing strain.

experiments and Super-Resolution STED Microscopy, and by combining these with his mechanical measurements showed that the recently discovered actin-spectrin periodic lattice in axons plays a prominent role in dictating axon mechanics. In another collaboration with Andrew Callan-Jones, a theoretical model for the axon was developed to argue that the spectrin molecules in the 1D lattice can undergo force dependent unfolding-refolding dynamics (like molecular bellows) and this results in a buffering of axonal stress. This model gives good agreement with experimental observation of the strain-softening solid-like response of the axon and the non-monotonous behaviour of the relaxation time vs strain curve. These results have now appeared in the prestigious journal eLife.

[Sushil Dubey, Nishita Bhember, Shivani Bodas (IISER-Pune), Aurnab Ghose (IISER-Pune), Sukh Veer, Serene Rose David, Andrew Callan Jones (University-Paris, Diderot) and Pramod Pullarkat]

Axonal shape instabilities

This experiment aims at understanding the shape stability of axons. Specific biochemical agents were used to depolymerise actin-filaments or microtubules (biopolymers present inside the axon) and study the resulting shape evolution. Two distinct responses were observed. (i) After microtubule depolymerisation the axon develop peristaltic radius modulations. (ii) When actin filaments are disrupted the axon exhibits a dynamic retraction front, which separates a thin region largely devoid of cytoskeletal components from a thick region into which these components are displaced. Interestingly, it was shown that both these shape dynamics may also be induced by local ablation of the axon using a nano-second laser pulse.

During previous years, Alka Bhat had shown the following: (a) Using genetic means to express fluorescent synaptic vesicles she had shown that transport in axons is not affected by beading suggesting that "traffic jam" may not be the cause for beading as previously suggested by others. She added further evidence to this by imaging intact microtubule tracks in a beaded axon and more importantly by imaging vesicle transport in beaded axons using Synaptophysin-GFP as a genetically incorporated fluorescent probe. (b) Laser ablation experiments conducted by Anagha Datar and later by Alka Bhat had shown that these shape changes can be induced by breakages in the cytoskeleton. Performing such experiments in presence of a microtubule stabilising agent showed that microtubule depolymerisation may ensue due to the fresh (unprotected) end created by ablation and this is the major cause for the shape evolution.

During 2018-19, further experiments like quantification of retraction rates and comparison with extent of beading was performed by Jaisha Bhanu. With collaborator Roberto Bernal more data was analysed, while the theoretical model developed in collaboration with Jacques Prost and Andrew Callan-Jones was improved. This model supports a membrane tension driven mechanism where the nature of microtubule depolymerisation dictates whether the axonal atrophy occurs via beading or retraction. It was shown that these instabilities are analogous to those seen in the de-wetting process of tapered wires.

During 2019-20 this work underwent revision and the experiments and model were further improved. Most notably, it was found that an analysis of the characteristic beading time can be used to extract the microtubule turnover rate in axons providing a powerful assay to study microtubule stability. In addition, PhD student Ashish Kumar performed calcium imaging after laser induced axotomy and presented his results. The article is now published in Biophysical Journal.

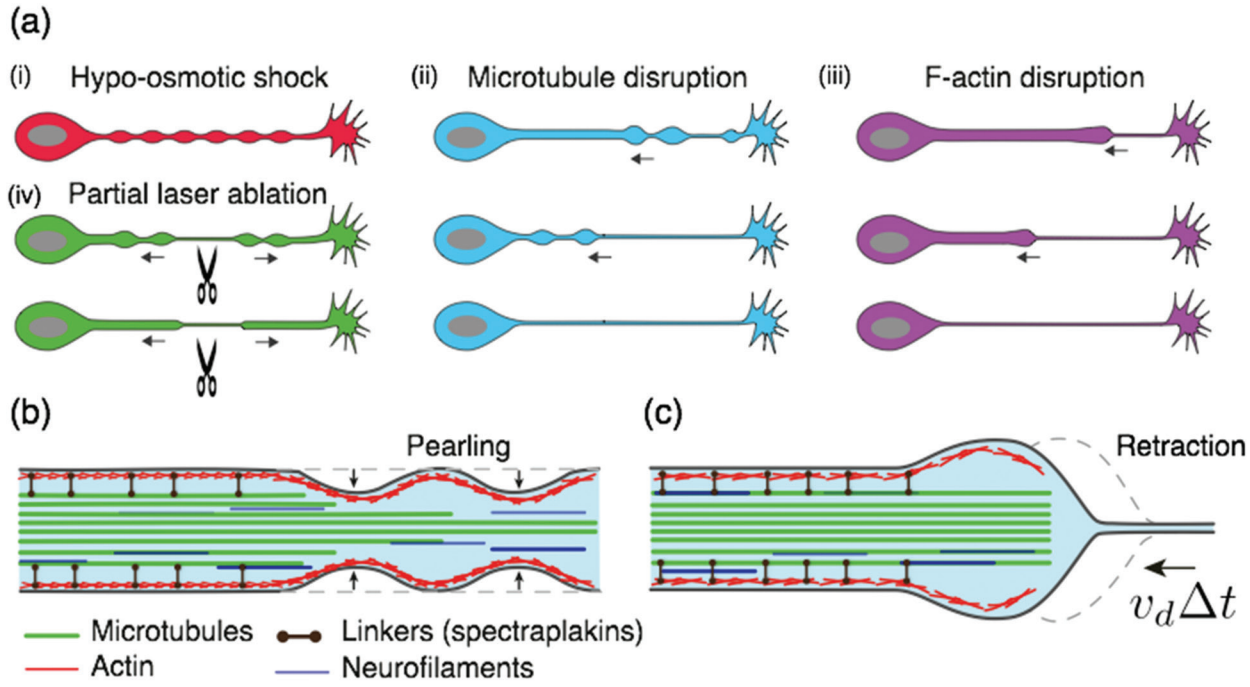


Figure 11. Schematic diagrams showing the variety of shape instabilities exhibited by axons under different perturbations.

[Anagha Datar(former PhD student at RRI), Jaisha Bhanu, Roli Srivastava(former project assistant at RRI), Alka Bhat, Ashish Mishra, Roberto Bernal (University of Santiago, Chile), Jacques Prost (Institute Curie, Paris), Andrew Callan-Jones (Institute Curie, Paris) and Pramod Pullarkat]

Mechanical properties of spider silk

Investigations of the mechanical properties of silk using the Micro-Extension Rheometer by Pramod Pullarkat and his PhD students Sushil Dubey and Sukh Veer along with Chinmay Joshi a Masters student from IISER Thiruvananthapuram has shown that silk exhibits strain softening behaviour up to 4% strain and thereafter shows strain stiffening. With Sayanthan Majumdar they developed a Fourier analysis method to obtain the frequency dependence of the viscoelastic moduli from the force relaxation data. They also determined the relaxation behaviour of silk, for the first time to their knowledge. The remaining experiments (cyclic ramps to measure energy dissipation) and analysis were completed during the past year and an article on this study was published in Soft Matter. Current efforts are towards developing a microscopic picture to explain the observations.

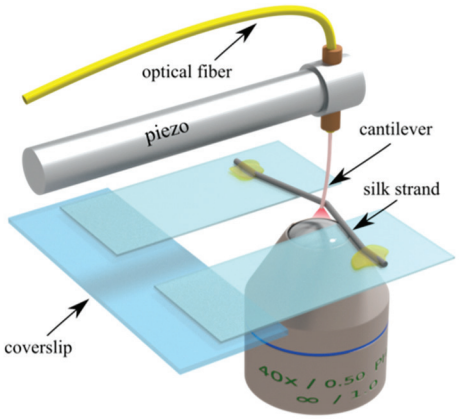


Figure 12. A schematic of the experimental scheme which uses the Micro-Extension Rheometer to study spider silk mechanics.

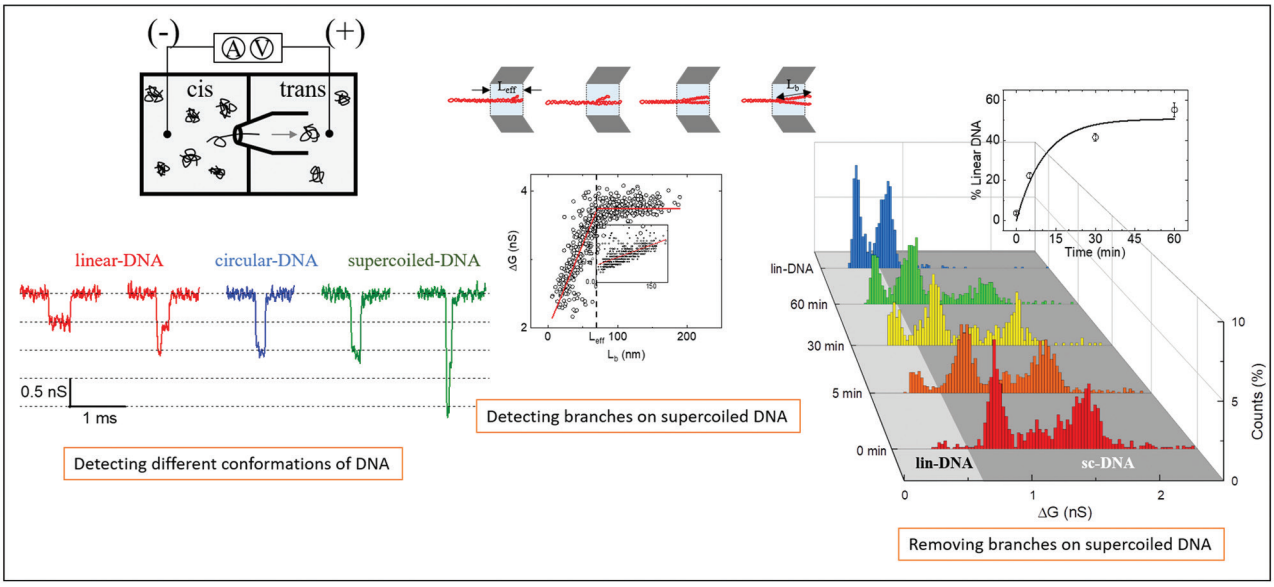
[Sushil Dubey, Sukh Veer, Chinmay Joshi (IISER-Thiruvanathapuram), Divya Uma (Azim Premji University, Bengaluru), Hema Somanathan (IISER-Thiruvananthapuram), Sayanthan Majumdar and Pramod Pullarkat.

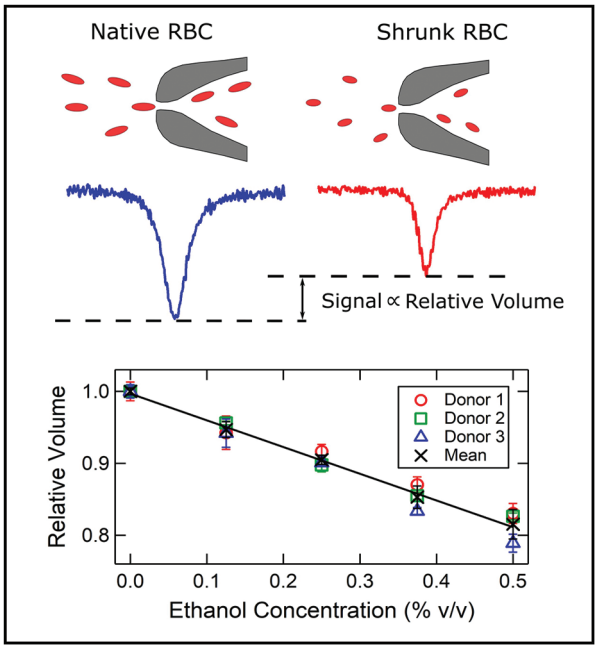
Nanoscale biophysics of Biological systems

The research interests of Gautam Soni's Nanoscale biophysics of biological systems laboratory at RRI are primarily guided by the role of force in biophysical structure formation and its synergy with functional dynamics. Research efforts are towards understand mechanisms of force-sensing as well as force-response of cells and molecules. They study this in biological model systems of protein-assembly, DNA-protein complexes as well as whole cell mechano-sensing. They use, as well as develop, novel bio- nano and micro scale tools to decipher biophysical principles governing role of forces in cellular as well as molecular assemblies.

During the past year, Gautam Soni and his students M Sumanth Kumar and Koushik S have used their inhouse built quartz nanopores to quantify branched DNA on supercoiled plasmid and have studied its enzymatic linearization.

Another research focus at the lab by Gautam Soni his students Saurabh Kaushik, Manohara M and collaborator Varadharajan Sundaramurthy was on measurement of alcohol dependent physiological changes in red blood cells using a novel high resolution electro-fluidic device developed in their lab. Alcohol exposure has been postulated to adversely affect the physiology and function of the red blood cells (RBCs). The global pervasiveness of alcohol abuse, causing health issues and social problems, makes it imperative to resolve physiological effects of alcohol on RBC physiology. Alcohol consumed recreationally or otherwise, almost immediately alters cell physiology in ways that is subtle and still unresolved. A novel high-resolution electro-fluidic device has been developed to quantitatively demonstrate changes in RBC cell-volume upon alcohol exposure. An exhaustive calibration of the device was carried out using model cells to measure and resolve volume changes down to 0.6 fL and RBCs shrinkage of 5.3% at 0.125% ethanol (legal limit) and a shrinkage of 18.5% at 0.5 % ethanol (lethal limit) exposure was found. Further, they also measured the time dependence of cell volume shrinkage (upon alcohol exposure) and then recovery (upon alcohol removal) to quantify shrinkage and recovery rates. This work presents the first direct quantification of temporal and concentration-dependent changes in red blood cell volume upon ethanol exposure. Their device presents a universally applicable high-resolution & high-throughput platform to measure changes in cell physiology under native and diseased conditions.





[Gautam Soni, Sumanth Kumar, Koushik S, Saurabh Kaushik, Manohara M and Varadharajan Sundaramurthy, NCBS, Bangalore]

Research: Knowledge Creation

Theoretical Physics

Theoretical Physics

Overview

Theoretical physics is an endeavour that attempts to make sense of the inner workings of nature, using the language of mathematics. The goal is to model and predict the behaviour of all systems from the very small (sub-atomic and smaller) to the very large (galaxies and beyond) that constitute this beautiful and complex universe that we live in. The Theoretical Physics (TP) group at RRI is actively pursuing research in the following areas: Statistical Physics, Quantum Gravity, Foundations of Quantum Mechanics and General Relativity. TP group has also forged a robust collaboration with experimental groups within RRI. The connection with Light and Matter Physics group is specifically in the areas of foundational questions in quantum mechanics, quantum information and nonlinear quantum optics. The overlap with the Soft Condensed Matter group is in areas such as biophysics, polymer physics and modelling stochastic search process. Additionally, RRI theorists have fruitful ongoing collaborations in the above research areas with both national and international peers.

Focus 2019-20

Statistical Physics

Statistical physics comprises a set of mathematical techniques that can be applied to a physical system to estimate its properties. Simply put, statistical techniques derive high-level (macroscopic) descriptions starting from low level (microscopic) ones after averaging out a lot of details. Finding the correct method of averaging out the details is key to the statistical method for investigation of physical systems. As an example, consider a box filled with gas. A correct statistical average of the momentum and position of individual atoms is mandatory for accurate descriptions of macroscopic quantities such as temperature and pressure. Researchers at RRI routinely employ statistical methods to understand physical systems.

Active particle dynamics

Active particles are self-propelled agents which consume energy from environment and convert it into directed motion. Apart from various interesting collective phenomena, active particles also show a lot of novel behaviour even at the level of individual particles. One of the main research interests is to study and characterize the properties of single active particles, using simple, analytically tractable models.

Long-time position distribution of active Brownian motion

Active Brownian Particles is one of the simplest models used to study the motion of active particles. Recently Urna Basu, and collaborators Satya N. Majumdar, Alberto Rosso and Gregory Schehr studied the late time dynamics of a single active Brownian particle in two dimensions and have shown that at late times, while the position probability distribution approaches a Gaussian form near its peak describing the typical diffusive fluctuations, it has non-Gaussian tails describing atypical rare fluctuations. They analytically computed the large deviation function and have shown that it still carries the trace of activity even at late times. Another way of detecting activity at late times is to subject the active particle to an external harmonic potential. In this case, they show that the stationary distribution undergoes a crossover, as the rotational diffusion constant increases, from a ring shape in the strongly active limit to a Gaussian shape in the strongly passive limit.
[Urna Basu and collaborators from Univ. Paris-Sud, France: Satya N. Majumdar, Alberto Rosso and Gregory Schehr]

Run-and-Tumble dynamics in two-dimensions

Run-and-Tumble particle (RTP) is another simple and well-studied model of active particles. Recently, Sanjib Sabhapandit, Urna Basu and PhD student Ion Santra have studied a set of RTP dynamics in two spatial dimensions where the particle orientation (i) can assume a set of n possible discrete values, and (ii) is a continuous variable. They have calculated exactly the marginal position distributions for n = 3, 4 and the continuous case and have shown that in all the cases the RTP shows a cross-over from a ballistic to diffusive regime. The ballistic regime is a typical signature of the active nature of the systems and is characterized by non-trivial position distributions which depends on the specific model. They have also characterized the atypical fluctuations by computing the large deviation functions explicitly which retain the signature of activity even at late-times.
[Ion Santra, Urna Basu and Sanjib Sabhapandit]

Exact stationary state of a run-and-tumble particle with three internal states in a harmonic trap

In another recent work, Urna Basu, Sanjib Sabhapandit and collaborators Satya N Majumdar, Alberto Rosso and Grégory Schehr have studied the position distribution of the n = 4 RTP model mentioned above in the presence of a harmonic trap. They have shown that the marginal position distribution undergoes a shape-transition as the

ratio β of the flip-rate and the trap-strength is changed. For < 1, the distribution has a double-concave shape and shows algebraic divergences both at the origin and at the boundaries. For > 1, the position distribution becomes convex, vanishing at the boundaries and with a single, finite, peak at the origin. They have also shown that for the special case = 1, the distribution shows a logarithmic divergence near the origin while saturating to a constant value at the boundaries.

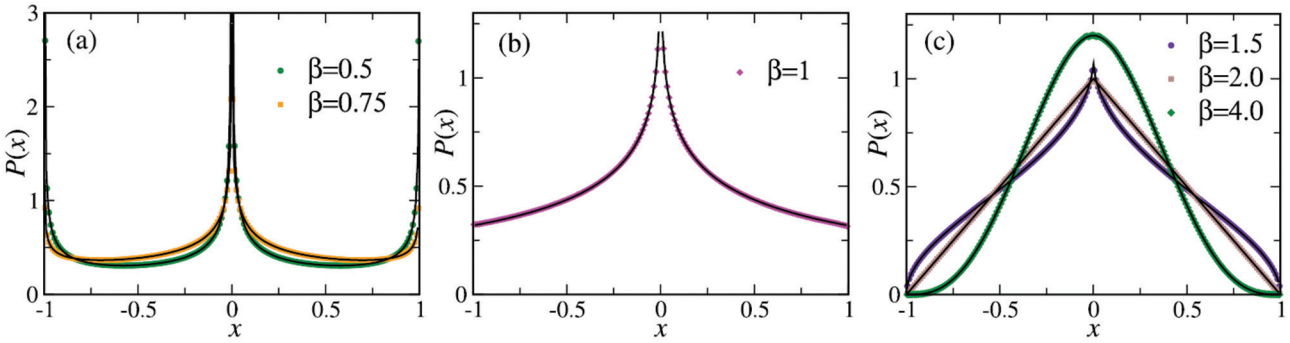


Figure 1. Stationary position distribution $P(x)$ as a function of x for the 3-state model for (a) β <1,(b) β =1,and(c) β >1.

[Urna Basu, Sanjib Sabhapandit and collaborators from Univ. Paris-Sud, France: Satya N Majumdar, Alberto Rosso and Grégory Schehr]

Orientational Distribution of an Active Brownian Particle: an analytical study

The orientational probability distribution of an active Brownian particle(ABP) at various time regimes was analytically studied by Supurna Sinha. The predictions resulting from this study can be tested against future simulations and experiments on an ABP.

The study of the non-equilibrium dynamical properties of an active Brownian particle has been of great current interest because of its relevance to many biological systems and driven soft matter systems. One of the challenges in the field has been to understand the orientational probability distribution of an ABP and is the motivation behind the present study. She used the Fokker Planck equation as a starting point for studying the orientational probability distribution of an Active Brownian Particle (ABP) in (d + 1) dimensions. This Fokker Planck equation admits an exact solution in series form which is, however, unwieldy to use because of poor convergence for short and intermediate times. A truncated version of this series is a reasonable approximation for long times. Through this work she presented an analytical closed form expression, which gives a good approximate orientational probability distribution, which is derived using saddle point methods for short times. However, it works well even for intermediate times. Thus, this study has resulted in simple analytical forms for the entire range of time scales for the orientational probability distribution of an ABP. The predictions from this study can be tested against future experiments and simulations probing orientational probability distribution of an ABP.

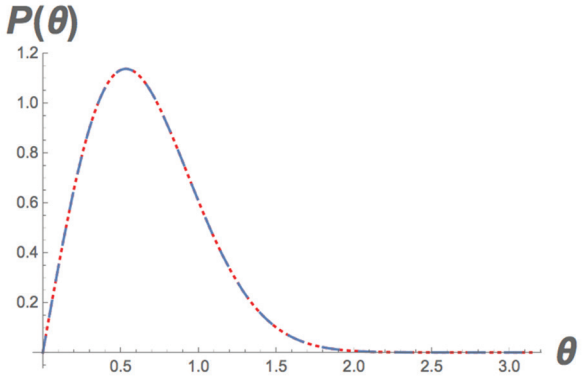


Figure 2. Orientational Probability Distribution of an Active Brownian Particle at time t=0.3. The blue dashed line is the Exact Orientational Probability Distribution, and the red dotted line is the short time approximate Distribution that has been analytically derived in the present study.

[Supurna Sinha]

Symmetric Exclusion Process under Dichotomous Stochastic Resetting

Stochastic resetting, which refers to intermittent interruption and restart of a dynamical process, has been a subject of immense interest in recent years. A particularly interesting question is how the presence of resetting affects interacting systems with many degrees of freedom. Recently, Urna Basu and Onkar Sadekar (visiting student at RRI) have studied the dynamics of symmetric exclusion process (SEP) in the presence of stochastic resetting to two possible specific configurations – with rate r_1 (respectively, r_2) the system is reset to a step-like configuration where all the particles are clustered in the left (respectively, right) half of the system. They have shown that this dichotomous resetting leads to a range of rich behaviour, both dynamical and in the stationary state. They calculated the exact stationary profile in the presence of this dichotomous resetting and have shown that the diffusive current grows linearly in time, but unlike the resetting to a single

configuration, the current can have negative average value in this case. For $r_1 = r_2$, the average current vanishes, and density profile becomes flat in the stationary state, similar to the equilibrium SEP. However, the system remains far from equilibrium. They characterized the nonequilibrium signatures of this 'zero-current state' and have shown that both the spatial and temporal density correlations in this zero-current state are radically different than in equilibrium SEP. Study of the behaviour of this zero-current state under an external perturbation has demonstrated that its response differs drastically from that of equilibrium SEP – while a small driving field generates a current which grows as $\sqrt{t}$, the zero-current state in the presence of dichotomous resetting shows a current $\sim t$ under the same perturbation. [Urna Basu and Onkar Sadekar (visiting student from IISER Pune, India)]

Dynamical correlations of conserved quantities in the one-dimensional equal mass hard particle gas

Sanjib Sabhapandit and collaborators Aritra Kundu and Abhishek Dhar studied a gas of point particles with hard-core repulsion in one dimension where the particles move freely in-between elastic collisions by preparing the system with a uniform density on the infinite line. The velocities of the particles were chosen independently from a thermal distribution. Using a mapping to the non-interacting gas, they analytically computed the equilibrium spatio-temporal correlations of the arbitrary integer powers of the velocities. The analytical results were verified with microscopic simulations of the Hamiltonian dynamics. Their results have shown that the correlation functions have ballistic scaling, as expected in an integrable model. [Sanjib Sabhapandit and collaborators from ICTS, Bengaluru: Aritra Kundu and Abhishek Dhar]

Entropy production for partially observed harmonic systems

The probability distribution of the total entropy production in the non-equilibrium steady state follows a symmetry relation called the fluctuation theorem. When a certain part of the system is masked or hidden, it is difficult to infer the exact estimate of the total entropy production. Entropy produced from the observed part of the system shows significant deviation from the steady state fluctuation theorem. This deviation occurs due to the interaction between the observed and the masked part of the system. A naive guess would be that the deviation from the steady state fluctuation theorem may disappear in the limit of small interaction between both parts of the system. In contrast, Sanjib Sabhapandit and collaborator Deepak Gupta investigated the entropy production of a particle in a harmonically coupled Brownian particle system (say, particle A and B) in a heat reservoir at a constant temperature [see Figure 3 (left panel)] . The system was maintained in the non-equilibrium steady state using stochastic driving. They studied the deviation from the steady state fluctuation theorem for the entropy production of a partial system of a coupled system when the coupling between particle A and B is infinitesimally weak. Furthermore, they considered a harmonically confined system, i.e., a harmonically coupled system of particle A and B in harmonic confinement [see Figure 3 (right panel)] and found that in the weak coupling limit, the entropy produced by the partial system (e.g., particle A) of the coupled system in a harmonic trap satisfies the steady state fluctuation theorem. They also performed numerical simulations to support the analytical results [see Figure 4].

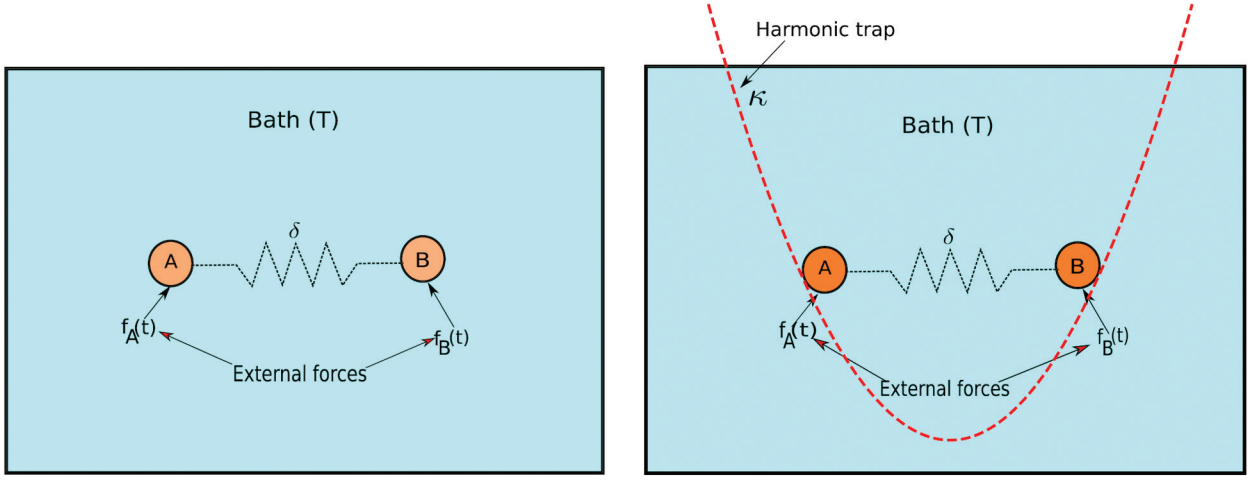


Figure 3. Left panel: Two Brownian particles (A and B) are coupled with a spring of coupling parameter $\delta = 2km/\gamma^2$ (dimensionless). The whole system is in contact with a heat bath of constant temperature T. The external stochastic Gaussian forces $f_A(t)$ and $f_B(t)$ are acting on the particles A and B, respectively. **Right panel:** The whole system in confined in a harmonic trap of strength $K = mk_0/\gamma^2$ (dimensionless).

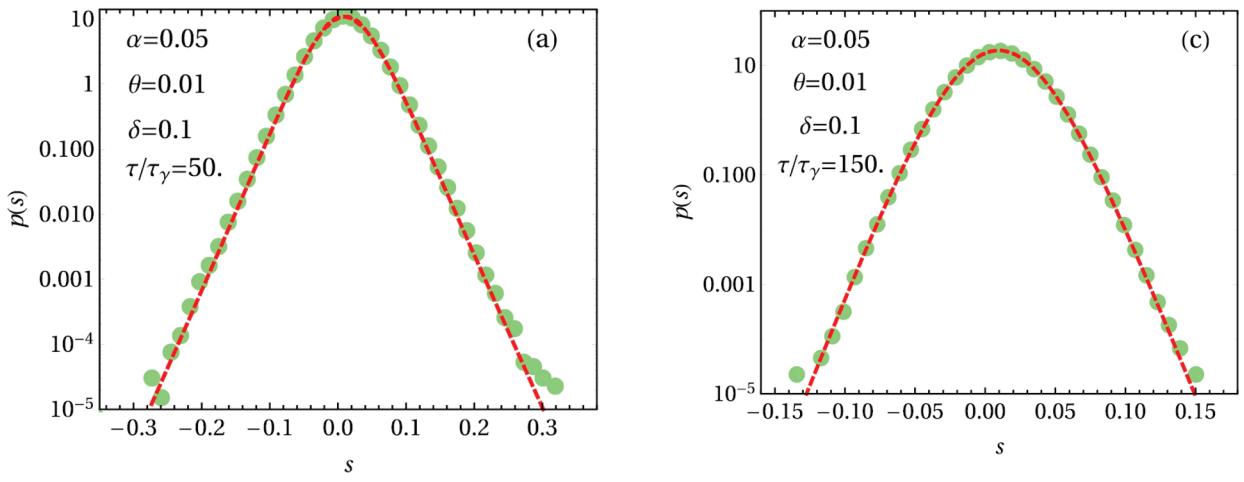


Figure 4. Comparisons of the analytical probability density function $p(s)$ (red dashed lines) with the numerical simulations (green circles) are shown for time $\tau/\tau_\gamma = 50$ [left panel] and $\tau/\tau_\gamma = 150$ [right panel].

[Sanjib Sabhapandit and Deepak Gupta (Universita´ di Padova, Italy)]

Quantum Brownian Motion: Drude and Ohmic Baths as Continuum Limits of the Rubin Model

The motion of a free quantum particle in a thermal environment is usually described by the quantum Langevin equation, where the effect of the bath is encoded through a dissipative and a noise term, related to each other via the fluctuation dissipation theorem. The quantum Langevin equation can be derived starting from a microscopic model of the thermal bath as an infinite collection of harmonic oscillators prepared in an initial equilibrium state. The spectral properties of the bath oscillators and their coupling to the particle determine the specific form of the dissipation and noise. During the past year Supurna Sinha, PhD student Ion Santra and collaborators Avijit Das, Abhishek Dhar and Urbashi Satpathi have investigated in detail the well-known Rubin bath model, which consists of a one-dimensional harmonic chain with the boundary bath particle coupled to the Brownian particle. They have shown how in the limit of infinite bath bandwidth, they get the Drude model and a second limit of infinite system-bath coupling gives the Ohmic model. A detailed analysis of relevant correlation functions, such as the mean squared displacement, velocity auto-correlation functions, and the response function were undertaken, with the aim of understanding the various temporal regimes. In particular, the quantum to classical crossover time scales where the mean square displacement changes from a $\sim \ln t$ to a $\sim t$ dependence was discussed. They relate this study to recent work using linear response theory to understand quantum Brownian motion.

[Avijit Das(ICTS, Bangalore), Abhishek Dhar(ICTS, Bangalore), Ion Santra, Urbashi Satpathi(ICTS, Bangalore) and Supurna Sinha]

Quantum Gravity

The construction of fully quantum mechanical description of the gravitational interaction remains the outstanding open problem in fundamental theoretical physics. Quantum gravitational effects are expected to be dominant in extreme situations such as at the Big Bang and deep inside Black Holes. Einstein's General Relativity identifies gravitation as arising with the geometry of space and time. Hence, a theory of Quantum Gravity is expected to revolutionise our very notions of spacetime and would herald a paradigm shift exceeding that following the discovery of Quantum Mechanics. Two different approaches to Quantum Gravity are pursued at RRI. One is a canonical continuum approach, Loop Quantum Gravity and the other is a discrete path sum approach, Causal Set Theory

Loop Quantum Gravity

One very successful approach to building such a theory goes by the name of Loop Quantum Gravity (LQG). It attempts to generalise the familiar techniques of quantum mechanics and quantum field theory and apply them to the context of gravitation. This generalization is technically and conceptually very intricate because, unlike the case of quantum field theory where the quantum fields evolve on a fixed spacetime, here it is the very geometry of spacetime which is dynamical. Hence one needs a generalization which does not rely on notions of a background fixed spacetime. While one has a fine understanding of how to describe quantum spatial geometry in LQG (`LQG kinematics'), a key open problem is how to describe quantum spacetime geometry (`LQG dynamics').

Technical description of Specific Work undertaken in this area during the past year:

The conservative techniques of LQG are those of canonical quantization wherein one splits spacetime into space and time, reformulates the Einstein equations as Hamiltonian equations on phase space and seeks to replace Poisson brackets between functions by commutators between their operator correspondents. One key issue is then how to achieve this in a manner in which spacetime emerges from space and time in this Hamiltonian description. Since there is no preferred choice of background time, each choice of time corresponds to a distinct dynamical evolution and the emergence of classical spacetime is tied to the consistency of these (infinitely many) distinct dynamical evolutions.

This consistency is captured by the particular structure of the Poisson Brackets between the Hamiltonians for these evolutions. Similarly, quantum spacetime is expected to emerge only if this algebraic structure is captured by the corresponding commutators. The commutator structure is very different than that encountered in known theories. Since full-blown gravity has a variety of complications, over the last decade Madhavan Varadarajan has focussed on an extremely non-trivial system which is obtained as a novel weak coupling limit of Euclidean General Relativity and which exhibits an algebra which is isomorphic to that of Euclidean gravity. Recently, he constructed a quantum representation for this system in which the intricate commutator structure is exactly of the type required. However, the resulting dynamics did not propagate quantum perturbations. This is in contrast to the propagation of perturbations such as gravitational waves in General Relativity. Accordingly, he defined a slightly modified quantum dynamics which does lead to vigorous propagations in the model. A key open issue is then to demonstrate that the modified dynamics captures the intricate algebraic structure associated with the emergence of quantum spacetime.

The problem displays several complexities beyond the non-propagating case. It is pertinent to note that the non-propagating case involved several years of sustained work, culminating in an over 90 page paper. While the propagating case is even more difficult, in work over the last year Madhavan Varadarajan has made significant progress through the introduction of several new ideas and techniques and expects a complete solution over the course of this year.

An anomaly free and propagating dynamics for a weak coupling limit of Euclidean gravity (In progress)

While Madhavan Varadarajan has made significant progress over the last decade in the construction of a propagating, spacetime covariant quantum dynamics in a model which captures many of the aspects of General Relativity, certain key complexities related to local symmetries of geometry in General Relativity are not present in the model. In this regard, the putative construction of such a dynamics for Quantum Euclidean General Relativity is widely accepted to be a very significant milestone in the field of Loop Quantum Gravity. Such a construction would be a necessary precursor to a treatment of the physically relevant Lorentzian case. A solution to this problem has eluded workers for almost three decades now. Madhavan Varadarajan is currently working on this problem and is hopeful of progress in the coming year stemming from the application of new tools and ideas which he developed over the last decade.
[Madhavan Varadarajan]

Causal Set Theory

Causal Set Theory (CST) is a manifestly covariant approach to quantum gravity, which assumes that spacetime is fundamentally discrete. CST is motivated by deep theorems in Lorentzian geometry, and gives primacy to the causal ordering of spacetime events. In CST the causal structure (which is a partially ordered set) is quantised. It posits that the continuum is an approximation to an ensemble of underlying locally finite partially ordered sets or causal sets.

Dimensionally Restricted Causal Set Quantum Gravity: Examples in Two and Three Dimensions

The search for a fully non-perturbative theory of quantum gravity has led to extensive activity over the past decade. The causal set approach has several advantages, since it is inherently covariant, so that observables are relatively easy to define. Almost a decade ago, Sumati Surya developed Markov chain Monte Carlo(MCMC) methods to study the dynamics of topologically trivial 2d quantum gravity, which paved the way for extensive work in this area. Recently there have been vast improvements in the numerical efficiency in calculating the causal set action, which is a significant time-sink in the MCMC simulations. This improved efficiency has now made it possible to simulate dimensionally restricted non-perturbative quantum gravity dynamics in 2 and 3 spacetime dimensions with non-trivial global spatial topology (S^1 in 2d and T^2 in 3d). In both cases, Sumati Surya and collaborator William Cunningham found a phase transition which separates the deep quantum regime from the continuum regime (Figures 5, 6). They characterized the phase transition using the expectation values of several covariant observables which acted as order parameters. These findings attest to a universal behaviour, characteristic of this class of non-perturbative theories of quantum gravity.

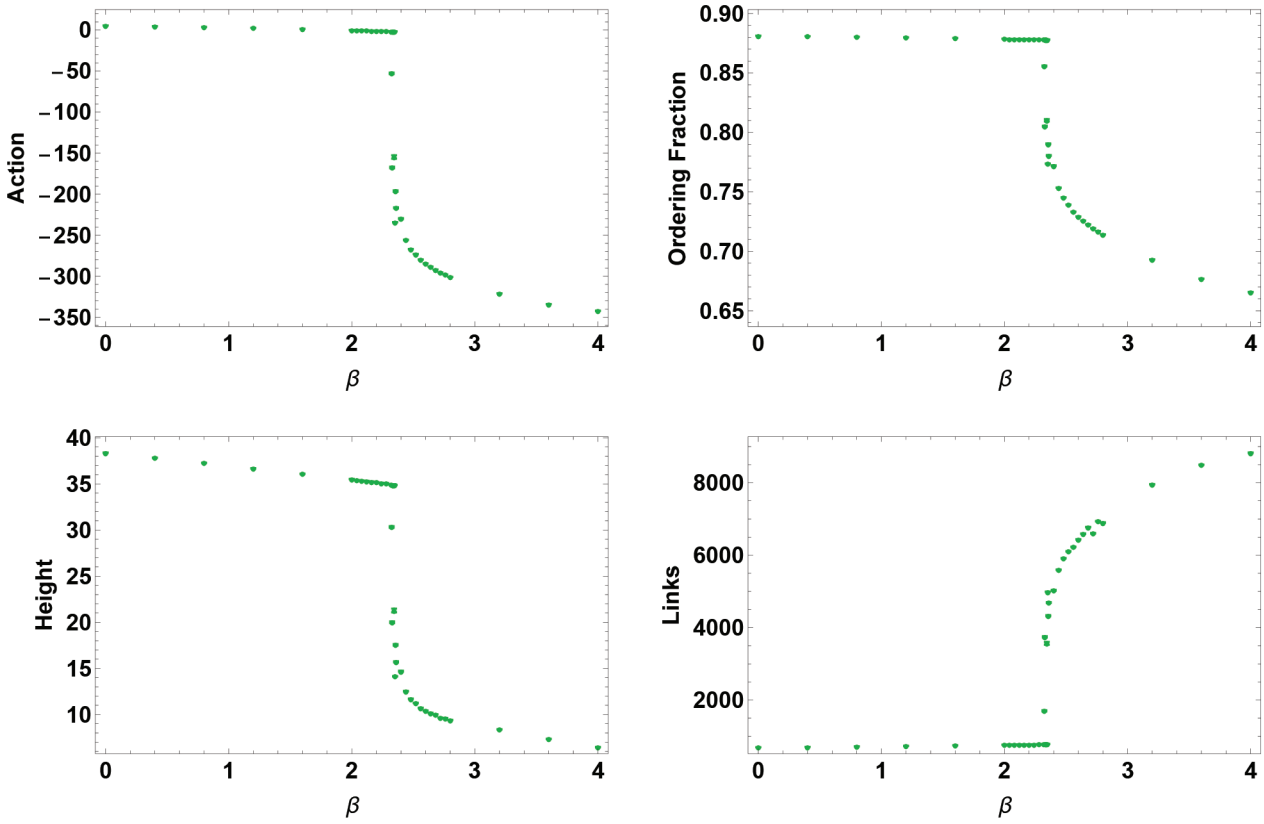


Figure 5. The phase transition for various observables in 2d

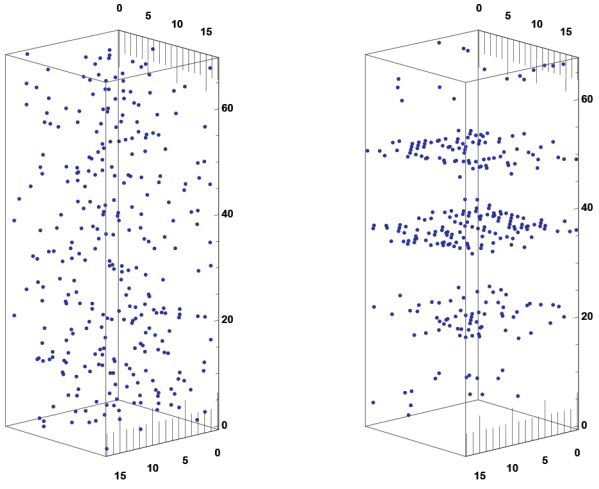


Figure 6. An example of a 3d configuration before the phase transition **(left)** and after the phase transition**(right)**. The configuration on the left is approximated by the flat spacetime $T^2 \times I$, while that on the right is pre-geometric and has no continuum counterpart. In particular, it is layered, with every element in a layer causally related to every element in the previous layer. It therefore has no particle horizons.

[Sumati Surya and William J Cunningham (Perimeter Institute for Theoretical Physics, Canada]

Sorkin Johnston Vacuum for a 2d scalar field in the Small Mass Approximation

An important feature of quantum field theory on a generic curved spacetime is the lack of a preferred vacuum. As was pointed out by Hawking and subsequently, Unruh, the choice of vacuum depends on the observer and is not in this sense fundamental. This reinforced the algebraic approaches to quantum field theory in curved spacetime, which are defined without reference to a vacuum. In the last decade or so, a new prescription has emerged for an observer-independent vacuum, the so-called Sorkin-Johnston or SJ vacuum. The central SJ eigenvalue problem was solved in 2d Minkowski spacetime by Sumati Surya and her PhD student Abhishek Mathur in the small mass limit (Figure 7). They constructed the corresponding SJ vacuum analytically and showed that it coincided with the massless rather than the massive Minkowski vacuum at the center of the diamond, even to next to leading order in the mass. This was confirmed by numerical simulations on the causal set which showed that the SJ massive vacuum matches the massive Minkowski vacuum only beyond a critical mass. In a Rindler-like wedge, moreover, rather than obtain the expected Rindler vacuum, the SJ vacuum approximates the mirror vacuum, as in the massless case. This study raises an interesting puzzle about the role of thermality in the SJ formulation.

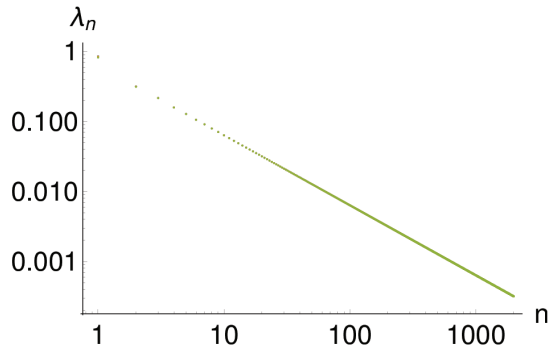


Figure 7. A log-log plot of the SJ spectrum with quantum number, for small mass
[Sumati Surya and Abhishek Mathur]

Entanglement Entropy for deSitter Horizons

An open question in horizon physics, which includes blackhole physics, is how much of the horizon entropy can be attributed to Entanglement Entropy (EE). The concept of EE was defined by Sorkin and collaborators for a quantum scalar field in the late '80s and shown to follow an area law when a UV cut-off is imposed. Interest in EE has been regenerated over the past decade, both in quantum gravity, especially string theory, as well as in condensed matter systems. About a decade ago, a spacetime entanglement entropy (SSEE) was defined by Sorkin. Using the Sorkin-Johnston vacuum, Sumati Surya and her PhD student Nomaan X along with collaborator Yasaman Yazdi have calculated the SSEE for de Sitter horizons in 2 and 4 dimensions using a causal set discretisation for a conformally coupled free scalar field. They found that not only is an area law satisfied with an appropriate truncation of the Sorkin-Johnston spectrum, but also that the SSEE satisfies complimentarity.

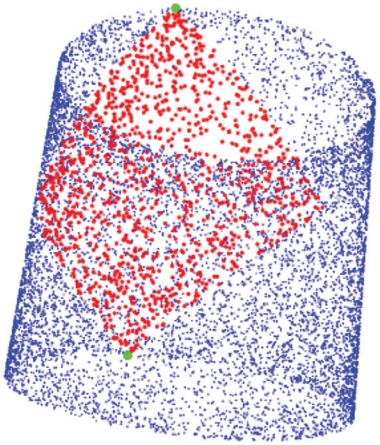


Figure 8. The spacetime entanglement entropy was calculated for the causal diamond in deSitter spacetime, and shown to be proportional to the de Sitter horizon area.
[Sumati Surya, Yazaman Yazdi (Imperial College, UK) and Nomaan X]

Classical and Quantum Foundations, Information and Optics

A Physical Perspective on Classical Cloning

The quantum no-cloning theorem states that an arbitrary quantum state cannot be cloned perfectly. During the past year, Anirudh Reddy, Supurna Sinha and Joseph Samuel investigated the issue of cloning of states in the classical domain and explicitly showed how perfect classical cloning can be implemented using Hamiltonians. They also investigated how statistical mechanical noise leads to imperfection while cloning classical states and have discussed possible experimental demonstrations of their ideas.

While the quantum no cloning theorem is a relatively well known idea, the notion of cloning in the classical domain is less explored. Thus it is challenging to address the issue of the process of cloning and its limitations in the classical domain. This is the motivation behind this study. The celebrated quantum no-cloning theorem states that an arbitrary quantum state cannot be cloned perfectly. This raises questions about cloning of classical states, which have also attracted attention. In this work, they present a physical approach to the classical cloning process showing how cloning can be realised using Hamiltonians. After writing down a canonical transformation that clones classical states, they have shown how this can be implemented by Hamiltonian evolution. They then propose an experiment using the tools of nonlinear optics to realise these ideas. Finally, to understand the cloning process in a more realistic context, they have introduced statistical mechanical noise to the system and studied how it affects the cloning process. While most of this work deals with linear systems and harmonic oscillators, they have given some examples of cloning maps on manifolds and have shown that any system whose configuration space is a group manifold admits a cloning canonical transformation.
[Anirudh Reddy, Supurna Sinha and Joseph Samuel]

Condensed Matter and Atomic, Molecular and Optical (AMO) Physics

Research at the Institute in Condensed Matter and AMO physics is towards understanding nonequilibrium quantum dynamics in solid-state and AMO systems applying physical laws, particularly the laws of quantum mechanics, electromagnetism, and statistical mechanics. While the topics of interest in condensed matter are disordered

systems, superconductors, and topological materials, the research in AMO is mainly in waveguide quantum electrodynamics and precision measurements using atomic vapors and ultracold atoms.

Pancharatnam-Zak phase

Overview :

Three decades ago, in a celebrated work, Zak found the geometric phase acquired by an electron in a one-dimensional periodic lattice as it traverses the Bloch band. Such a geometric phase is useful in characterizing the topological properties and the electric polarization of the periodic system. It was later understood that Zak's expression is gauge dependent and yields an arbitrary value for the geometric phase. In a recent work Vivek Vyas, Dibyendu Roy, and Joseph Samuel have explained that the gauge dependence of Zak's expression arises from the assumption that the electron's adiabatic motion is cyclic in the notion of recurrence of the density matrix under time evolution. On the contrary, the underlying system displays cyclicity in a generalized sense when the observables rather than density matrix return in the course of evolution. Using such a concept of generalized cyclicity, they have derived a correct and consistent expression for the geometric phase in this system called the Pancharatnam-Zak phase. They have shown that Pancharatnam-Zak phase is a quintessentially geometric object, displaying gauge invariance, and correctly classifies the Bloch bands of the lattice. A filled band extension of the Pancharatnam-Zak phase was also constructed and carefully investigated.

Details :

With the celebrated work of Berry (1984), the notion of the geometric phase came to prominence and was soon found to be manifesting in diverse areas of physics. Berry considered an adiabatically evolving quantum system, which returned to its initial physical state in the course of evolution. He made a profound observation that such a state on its return can acquire a non-trivial observable phase, solely of geometric origin. Such a geometric phase was found to possess two crucial properties: (a) that of gauge invariance, which means being insensitive to the convention employed in studying the time evolution of the system; and (b) independence of the parametrization employed to define the physical state at any given time.

Motivated by Berry's work, Zak in a milestone paper (1989) attempted to apply this notion of the geometric phase to study the motion of an electron in one-dimensional periodic lattice under the influence of a weak electric field (see Figure 8). The expression of the Zak phase, which is claimed to be the geometric phase acquired by an electron, was obtained in this work. This work quickly received significant attention, and motivated researchers to employ the Zak phase for characterizing the energy bands in such periodic lattices. It is upon this idea that the current understanding of the topological materials and quantum Hall effect is based, as also the modern theory of polarization in dielectrics. However, the Zak phase is known to suffer from serious flaws, it is known to be gauge dependent, and its value alters as per the choice of convention employed in evaluating it. These flaws completely demolish the claim that the Zak phase is a geometric phase.

Given such a scenario, it is natural to ask about the correct geometric phase, acquired by an electron in such a periodic lattice system. In a recent work, Vivek Vyas, Dibyendu Roy and Joseph Samuel answer this question by providing an accurate and consistent derivation of the geometric phase, which they call the Pancharatnam-Zak phase. They have employed the concept of the geometric phase in such a system defined in its generality, as initially conceived by Pancharatnam, unlike the other known attempts and have shown that the Pancharatnam-Zak phase so obtained possesses all the necessary invariance properties under gauge and coordinate transformations. The underlying topological and geometrical structure giving rise to the Pancharatnam-Zak phase were also uncovered in this process. It naturally led them to construct a filled band generalization of the single electron Pancharatnam-Zak phase for dielectrics. Being an experimentally measurable phase, they believe that both single electron and filled band Pancharatnam-Zak phases are accessible to controlled quantum experiments.

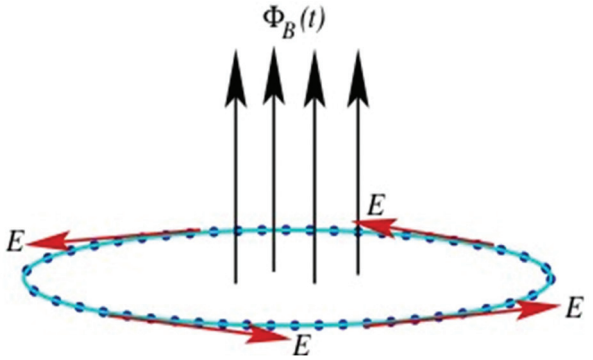


Figure 8. Schematic representation of the periodic lattice system studied in this work. The cyan curve represents the periodic lattice, whereas the black arrows depict the magnetic flux $\Phi_B(t)$. The red arrows show the tangential electric field experienced by the electrons in the lattice.
[Vivek Vyas, Dibyendu Roy and Joseph Samuel]

Amplification and cross-Kerr nonlinearity in waveguide quantum electrodynamics

Overview:

Dibyendu Roy and his PhD student Athul Vinu have explored amplification and cross-Kerr nonlinearity by a three-level emitter (3LE) embedded in a waveguide and driven by two light beams. The coherent amplification and cross-Kerr nonlinearity were demonstrated in recent experiments, respectively, with a V and a ladder-type 3LE coupled to an open superconducting transmission line carrying two microwave fields. In this work, they have considered Λ, V, and ladder-type 3LE, and compared the efficiency of coherent and incoherent amplification as well as the magnitude of the cross-Kerr phase shift in all three emitters. The Heisenberg-Langevin equations approach was applied to investigate the scattering of a probe and a drive beam both initially in a coherent state. Particularly they calculated the regime of the probe and drive powers when the 3LE acts most efficiently as a coherent amplifier, and have derived the second-order coherence of amplified probe photons. Finally, the Kramers-Kronig relations was applied to correlate the amplitude and phase response of the probe beam, which were used in finding the coherent amplification and the cross-Kerr phase shift in these systems.

Details:

The waveguide quantum electrodynamics (WQED) is a relatively new research discipline where strong, effective interactions between propagating single photons can be realized by employing strong light-matter coupling inside waveguide geometries (see, Rev. Mod. Phys. 89, 021001 (2017)). The coherent amplification and cross-Kerr nonlinearity in WQED were demonstrated in recent experiments, respectively, with a V and a ladder-type three-level emitter (3LE) coupled to an open superconducting transmission line carrying two microwave fields. Both the amplification and cross-Kerr effect have many potential applications for quantum sensing and metrology, including single-photon detection and generation of efficient entanglement between photons.

In this work, they consider Λ, V, and ladder-type 3LE (see Figure 9), and compare the efficiency of coherent and incoherent amplification as well as the magnitude of the cross-Kerr phase shift in all three emitters. The Heisenberg-Langevin equations approach was used to investigate the scattering of a probe, and a drive beam both initially in a coherent state. While the amplitude response of a transmitted probe field in the presence of a drive field gives a measure of the coherent amplification, a difference in the phase response of the transmitted probe field in the presence and absence of a drive field was used to quantify cross-Kerr interaction between the probe and drive fields. Particularly they calculated the regime of the probe and drive powers when the 3LE acts most efficiently as a coherent amplifier, and have derived the second-order coherence of amplified probe photons.

The previous studies have investigated coherent amplification and cross-Kerr nonlinearity as separate phenomena. Through this work they were able to show a connection between them by correlating the amplitude and phase response of the probe beam, which are used in finding the coherent amplification and the cross-Kerr phase shift in these systems. They primarily identified a regime of probe powers when a measurement of amplitude response of probe transmission as a function of probe beam detuning can be used to derive the exact phase response of the probe beam. Therefore, their analysis opens up an exciting possibility for the examinations of amplification and cross-Kerr nonlinearity.

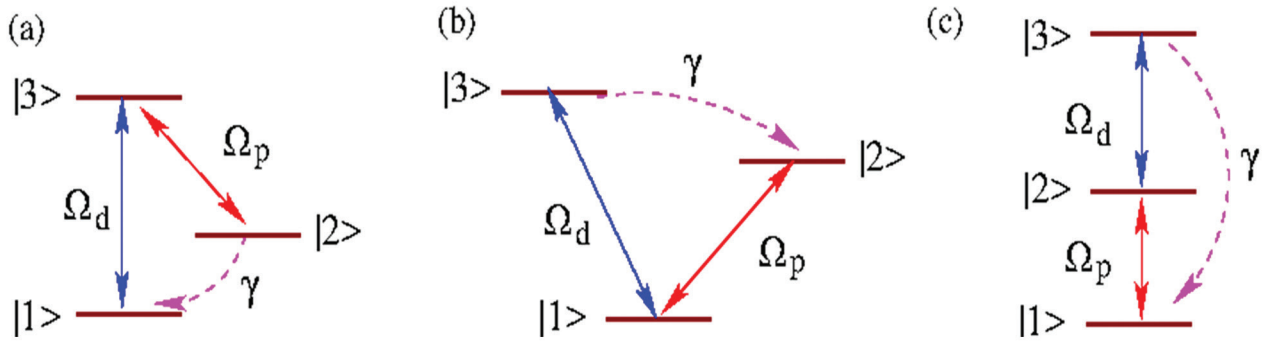


Figure 9. Cartoon of 3LEs with levels |1>, |2>, |3>. Three different arrangements for the coupling of probe (red arrow) and drive (blue arrow) beams with the allowed transitions they make (a) Λ, (b) V , and (c) ladder-type configuration of the 3LE. Here, Ωp and Ωd are respectively the Rabi frequency of the probe and drive beam, and γ denotes the strength of non-radiative decay.

[Athul Vinu and Dibyendu Roy]

Publications

Scientific staff and students of the Raman Research Institute publish their research activities carried out over the year in reputed 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 Astrophysical Journal, Astrophysical Journal Supplement Series, Astrophysical Journal Letters, Astronomy and Astrophysics, Current Science, Journal of Cosmology and Astroparticle Physics, Monthly Notices of the Royal Astronomical Society, Nature Astronomy and Physical Review D.

The Soft Condensed Matter group has its work published in Acta Crystallographica, ACS Applied Nano Materials, Applied Catalysis B: Environmental, Biophysical Journal, Bulletin of Materials Science, Carbon, Ceramics International, Chemical Physics Letters, Chemistry Select, Food Chemistry, Frontiers in Cell and Developmental Biology: Cell Adhesion and Migration, Journal of Applied Crystallography, Journal of Environmental Chemical Engineering, Journal of Physical Chemistry C, Journal of Molecular Liquids, Journal of Molecular Structure, Journal of Physics: Condensed Matter, Langmuir, Liquid Crystals, Microchemical Journal, Molecular Crystals and Liquid Crystals, Nano Express, Nature Communications, New Journal of Chemistry, Phase Transitions, Photochemical and Photobiological Sciences, Physical Chemistry Chemical Physics and Soft Matter.

Publications of the Light and Matter Physics group can be found in European Physical Journal D, Journal of Materials Science: Materials in Electronics, Journal of Optical Society of America B, Materials Chemistry and Physics, Nature Communications, New Journal of Physics, Optics & Laser Technology, Optical Materials, Optics and Photonic News, Optics Express, Optics Letters, Optik: International Journal for Light and Electron Optics, OSA Continuuum, Physical Review A, Physical Review Letters, Quantum Information Processing, Scientific American and Spectrochimica Acta Part A-Molecular and Biomolecular Spectroscopy.

Theoretical physicists at RRI use journals like Classical and Quantum Gravity, Europhysics Letters, Frontiers in Physics, International Journal of Modern Physics A, Journal of High Energy Physics, Journal of Statistical Mechanics: Theory and Experiment, Journal of Physics A: Mathematical and Theoretical, Living Reviews in Relativity, Physical Review E, Physics letters A, Pramana and others as a medium to share their knowledge with the national and international scientific community.

129 papers with RRI members as authors and/or co-authors were published during 2019-20. There were 4 publications in conference proceedings and 18 publications 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. During the past year, RRI members wrote 3 book chapters. 3 popular science articles were published in Desh, Research Matters and Scientific American.

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

Grants, Fellowships and Awards

	Name	Extramural grant	Details
1	Sadiq Rangwala	CEFIPRA proposal 5404	Project title: LORIC - LOng Range Interactions in ultraCold gases. Indian PI – Sadiq Rangwala, French-PI - Olivier Dulieu (Laboratoire Aime Cotton, France) and Bruna Labutthie-Tolra (Laboratoire de Physique des Lasers, France) Total grant money EUR 279,400, of which RRI component is INR 90,89,135. Project Duration: March 2016 - December 2019.
2	Biswajit Paul	ISRO grant for POLIX	Project title: Development of "X-ray Polarimeter experiment (POLIX) Payload" Total grant money: INR 9,50,00,000 Received so far: INR 6,07,56,933 Project start date: September 2017
3	Sanjib Sabhapandit	CEFIPRA Proposal 5604-2	Project title: Extreme events and large deviations in strongly correlated many body systems. PI's - Abhishek Dhar (ICTS, TIFR), Gregory Schehr (LPTMS, Orsay) Co-PI – Sanjib Sabhapandit Total grant money: INR 33,99,336, RRI share: INR 65, 000 Project Duration: December 2016 – November 2019
4	Urbasi Sinha	ISRO – QKD grant	Project title: Development of a prototype for satellite based secure quantum communication PI: Urbasi Sinha Total grant money: INR 27,00,00,000 Received so far: INR 10,76,96,288 Project started in December 2017
		India Trento Programme of Advanced Research (ITPAR)	Project title: A cheap, light, integrated source for QKD in an integrated photonic circuit PI: Urbasi Sinha Co-PI: Dipankar Home, Guruprasad Kar, Prasanta Panigrahi Total grant money: INR 1,61,13,520 Received so far: INR 57, 03, 520 Project started in February 2019
		DST - QuEST	Project title: Long distance quantum communications: Repeater and Relay technologies PI: Urbasi Sinha Co-PI: Arun K Pati, Ujjwal Sen, Aditi Sen-De Total grant money: INR 2,17, 60, 000 Received so far: INR 54, 50, 000 Project started in April 2019

	Name	Extramural grant	Details
		MEITY	Project title: Centre for Excellence in Quantum Technology PI (from RRI): Urbasi Sinha Co-PI (from RRI): Saptarishi Chaudhuri, Sadiq Rangwala, Dibyendu Roy Total grant money: INR 10,00,00,000 Received so far: INR 7,76,96,000 Project started in April 2020
5	Biman Nath	Indo-Russian grant No P270	Project title: The 500 parsecs around the galactic center PI's: Biman Nath , Yuri Shchekinov, Lebedev Physical research Institute, Moscow, Russia Total grant cost: INR 5,00,000 Received so far: INR 2,50,000 Project Duration: Sep 2017 – August 2019
6	Shiv Sethi	Indo – Russian grant through DST – RFBR INT/RUS/RFBR/P-276	Project title: Probing the reionization epoch and the high redshift IGM Indian PI : Shiv Sethi, Russian PI: Dr. Evgenii O. Vasiliev, Southern Federal University, Rostov Total grant money: INR 4,65,200 Received so far: INR 2,32,600 Duration: September 2017 – August 2019
7	Gautam Soni	Grand challenges India BDTD/08/2019	Project title: High throughput electrical detection of Malaria infection in single RBC's under low parasite density Total grant money INR 50,00,000 Received so far INR 38,00,000 Project duration: January 2018 – March 2020 Prototype for electronic mass screening device for Point-of-Care diagnostic of Sickle Cell Diseases Total grant money: INR 46,49,000 Received so far: INR 33,14,000
8	K S Dwarakanath	IUSSTF / JC-014 / 2017	Project title: Investigating dark matter and star formation in the outer disks of galaxies using UV, optical and 21 cm radio observations Indian PI: Mousumi Das (IIA), Co-PI K S Dwarakanath, USA PI: Stacy McGaugh (Case Western), Co-PI James Schombert (U Oregon) Total grant money: INR 30,29,600 Duration: March 2018 to February 2020.
9	Pramod Pullarkat	BT/PR23724/ BRB/10/1606/2017	Project title: Mechanobiology of cell adhesion under dynamic shear. PI – Namrata Gundiah (IISc, Bangalore), CoPI's – Pramod Pullarkat, Gautam Menon (IMSc, Chennai) Duration: starting from 17-05-2018 for three years Total amount: INR 95.884 lakhs Received so far: INR 20,57,000

	Name	Extramural grant	Details
10	Ranjini Bandyopadhyay	DST-SERB Grant EMR/2016/006757	Project title: Understanding the jamming dynamics and nonlinear viscoelasticity of non-equilibrium viscous liquids with non-linear dielectric and rheo-dielectric studies". Co-PI: Paramesh Gadige,c SSIHL, Andhra Pradesh Total amount: INR 47,44,000 Received so far: INR 23,96,500 Project started in 2019
11	Saurabh Singh, Mayuri S Rao, Jishnu Nambissan	ISRO Grant-in-Aid	Project Title: Pre-project activities for PRATUSH (Probing ReionizATion of the Universe using Signal from Hydrogen) PIs: Saurabh Singh (RRI, McGill University), Mayuri S. Rao (RRI, Lawrence Berkeley National Lab) and Jishnu Nambissan T. (RRI) Grant Amount: INR 36,00,000 Received so far: INR 36,00,000 Start date: March 13, 2019
12	Reji Philip	SERB – TARE Program	Project title: Femtosecond Laser-Induced Breakdown Spectroscopy (fs-LIBS) for Multi-elemental Compositional Analysis Mentor: Reji Philip Teachers Associate: Anoop KK Total amount: INR 18,30,000 RRI share: INR 3,35,000 Date Started: 26.11.2018

	Name	Fellowship	Details
1	Dibyendu Roy	SERB-Ramanujan Fellowship	Fellowship Start Date: 18.1.2016. Received so far: INR 58,60,000 Duration: 5 years.
2	Sumati Surya	Visiting Fellowship, Perimeter Institute	This fellowship will fund multiple visits to Perimeter Institute for a period of three years starting in 2019
3	Urbasi Sinha	Homi Bhabha fellowship Simons Emmy Noether fellowship	INR 25,000 per month plus contingencies for travel/ books connected with research Duration: July 2017 to July 2019. This fellowship will fund visits to Perimeter Institute for a duration of upto one year.
4	Sayantan Majumdar	SERB Ramanujan Fellowship	Total research grant amount: INR 38,00,000 Duration: 5 years Received so far: INR 7,60,000

	Name	Fellowship	Details
5	E Krishnakumar	Raja Ramanna Fellowship	Total Fellowship Amount: 40,50,000 Received so far: 25,50,000 Duration: 3 years
6	Urna Basu	SERB Ramanujan Fellowship	Total research grant amount: INR 38,00,000 Duration: 5 years Received so far: INR 7,60,000 Duration: 5 years

Awards

Sadiq Rangwala

Sadiq Rangwala is recipient of the P K Iyengar Memorial Award for Excellence in Experimental Physics. This award has been given by the Indian Physics Association in recognition of his "innovative experimental work in area of interactions between cold atoms and ions."

Saurabh Singh

- Best thesis award (Kumari L.A. Meera Memorial Medal)
- Justice Oak Award for Outstanding Thesis in Astronomy by Astronomical Society of India for 2019 (awarded in ASI meeting 2020).
- IOP Publishing Top Cited Author Award (India) for his article "First Results on the Epoch of Reionization from First Light with SARAS 2" (Singh et al., 2017, Astrophysical Journal, 845L, 12).

Sumanth Kumar

Sumanth Kumar (SCM) was awarded a travel grant under the Department of Biotechnology's Conference, Travel, Exhibition and Popular Lectures (DBT-CTEP) scheme. With this grant Sumanth attended the "64th Annual Meeting of the Biophysical Society" in San Diego, California, USA.

Research Facilities

Electronics Engineering Group

The members of the Electronics Engineering Group (EEG) form the backbone for all the engineering activities of the Institute. They have been taking part actively by building instrumentation for the research experiments undertaken by the scientific groups across the campus. Over the past couple of decades, technical staff of the group have made remarkable contributions which helped both the scientific staff as well as the Institute make significant progress in carrying out fundamental research in various diversified branches of science. It has also helped build both national and international facilities dedicated for scientific research in different core fields of physics. The group engages itself in developing and adopting state-of-the-art in engineering and technology in its various developmental activities. In the recent past, the group has been gaining expertise in specialised fields like RF over fiber (RFoF), Graphics Processing Units (GPU) and RF system on chip (RFSoC).

During 2019-20, the Electronics Engineering Group contributed to several on-going research projects of the Institute which include i) Polarimeter in X-ray ii) Brain Computer Interface (BCI) system for impaired patients and iii) analog and digital receiver systems for experiments in the field of observational Cosmology. Given below are the highlights of its contribution to each one of them.

1. Innovative antenna design for detecting Cosmic Dawn signal

Cosmic Dawn, in the thermal history of Universe, marks an important period. It is during this period that the first generation Stars and Galaxies were born. Nature of these sources and the physics of intergalactic medium during this time still remain uncertain. The global red-shifted 21cm signal is considered as an important tool to probe these astrophysical aspects. Since this signal is predicted to be extremely weak compared to the Galactic and Extragalactic foregrounds, detection of it using an antenna is an engineering challenge. A floating cone-disc antenna with an octave bandwidth in the frequency range 43.75–87.5 MHz has been designed and developed for the detection of the cosmological Cosmic Dawn signal. The innovations in the design are i) making the dimensions of the antenna electrically small ii)making monopole design so that feed point is at the antenna base iii) making the structural dimensions vary uniformly from the feeding point in order to minimize surface current reflections at structural discontinuities and iv) carefully choosing the design frequency and structural parameters so as to keep the resonance beyond the band of operation. Most importantly, the antenna was designed for operation over the surface of a water body of high permittivity to improve efficiency and avoid measurement errors from inhomogeneities in the medium beneath the antenna.

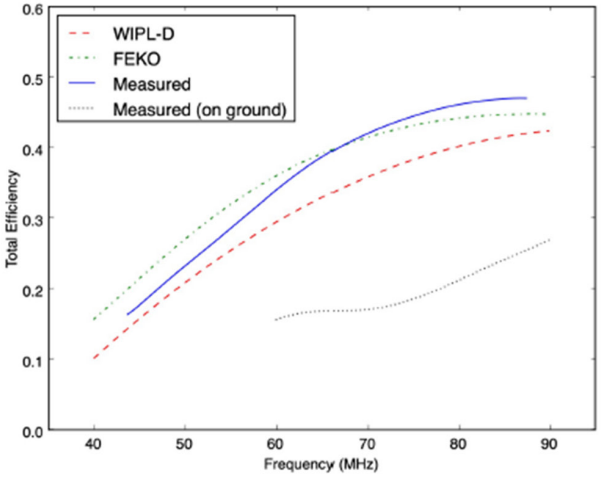


Figure 1. (Left) Photograph of the cone-disc antenna with raft deployed on the water surface of a lake. **Figure 2. (Right)** Measured total efficiency of the antenna. Also shown are efficiencies expected from WIPL-D and FEKO electromagnetic modelling. The total efficiency measured on real earth is also shown for comparison.

Figure 1 shows the photograph of the fabricated cone-disc antenna deployed on the water surface of a lake. The antenna is placed on a raft made of electromagnetically transparent Styrofoam material. Figure 2 shows the total efficiency measured on the water surface along with expected efficiency from electromagnetic modelling in WIPL-D and FEKO. The total efficiency measured when antenna was deployed on the real earth is also shown for comparison.

2. Hybrid FPGA-GPU based Correlation Spectrometer

Electronics Engineering Group has been involved in developing a wide band and high dynamic range hybrid FPGA-GPU based correlation precision spectrometer. This correlator is expected to be used in the detection of cosmological signal orders of magnitude weaker than the sky background imprinted in the spectrum of the cosmic microwave background radiation.

Combination of high bandwidth FPGA and high data reduction capability of GPU along with high throughput networking hardware results in a high performance device capable of processing massive data efficiently in real time. Such a heterogeneous architecture helps overcome several critical issues inherent to FPGAs. As a result, this has found several applications involving computer graphics, image processing, and algorithms for processing large blocks of data in parallel. Salient features of GPU such as i) ease of scalability i.e FFT size can be easily altered if required, without sacrificing any timing requirement ii) significant reduction in computation time iii) use of floating point arithmetic in GPU to overcome the error due to finite word length limitation of fixed point FFT implemented FPGA, are making this hybrid concept more attractive and efficient.

The hybrid correlation F-X spectrometer developed in-house at the Raman Research Institute has a high speed ADC from e2V and GeForce GTX 1050 GPU. ADC is used to digitize analog signal of 2 GHz bandwidth and channelize them to produce 1024 point both auto and cross power spectra in GPU and further average about 2048 of them. SX315T Virtex 6 FPGA is used to handle high-speed data streaming from ADC, packetize them and transfer to GPU.

The performance of the hybrid spectrometer was evaluated only in burst mode because of the computational resource and bandwidth limitations of GPU. The hybrid could produce successfully both self and cross power spectra of 2 GHz band signal However, its limited performance in timing is attributed to its lower end version. It could be improved with high speed GPUs like P100 / V100 and state-of-the-art server computers. C programs have been developed in Compute Unified Device Architecture (CUDA) - a parallel computing platform for processing the data.

3. Progress in the Brain Computer Interface system for patients with impaired movements

Electronics Engineering group is making continuous progress towards developing a simple, compact and easy to use brain computer interface system for paralysed patients. The system is being used by the patients to operate a word speller for communication and to command an output device for motion. Steady State Visually Evoked Potentials (SSVEP) are effectively used to perform the above operations. Trials on healthy subjects are being made in an identified hospital to evaluate the system being built. Data acquired is being analysed and inferred and also used for further improvement of the system. Appropriate changes in the stimulus are being made specifically for patients lying on the bed. As part of the development, a stable linear robotic arm has been designed for a specific operation. It was fabricated completely in-house and successfully demonstrated for its functionality.

4. X-ray Telescope in Space : To study polarization of X-Rays from cosmic sources

Raman Research Institute in collaboration with Indian Space Research Organization (ISRO) will be launching an X-ray telescope (also known as X-ray polarimeter – POLIX) into space for measuring the polarization of X-rays from cosmic sources in the energy band 5-30 keV. It is the most economical payload being developed inhouse for conducting research in X-ray astronomy.

Some of the subsystems of X-ray polarimeter like ground check-out system, base plate, scatterer and shield have been fabricated as qualification model and tested successfully. The same components are also being fabricated as flight model. In addition, wiring of detectors for the flight model are completed and are being subjected to vibration test along with all mechanical components. Electronics Engineering Group has been gaining experience in the scientific payload design and its conversion from qualification model to flight model.

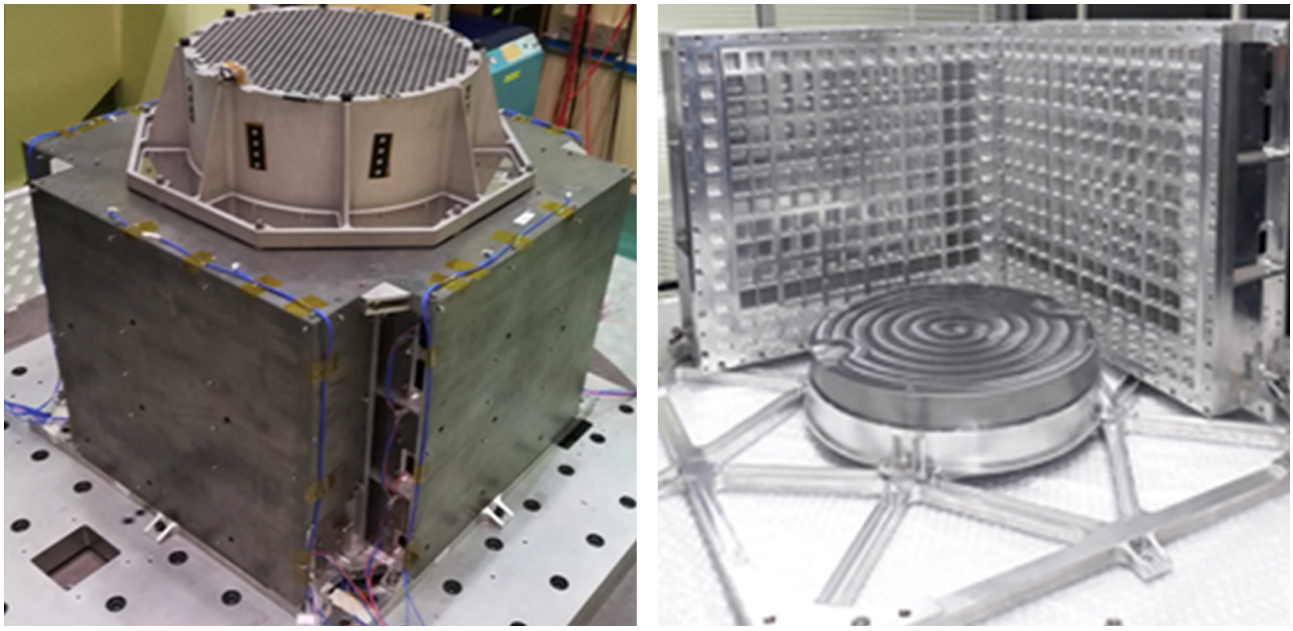
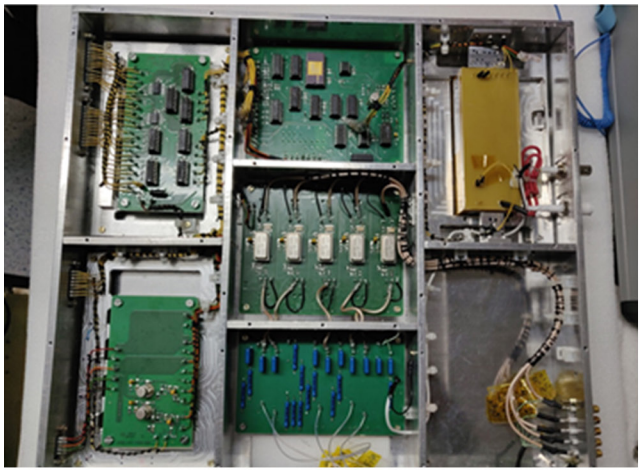


Figure 3. Photograph of POLIX detector system



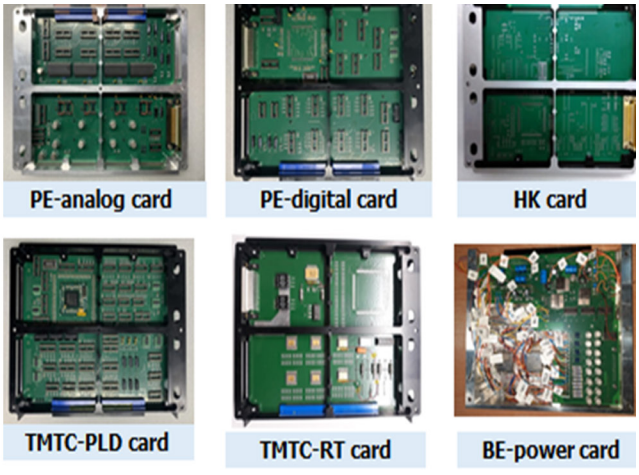


Figure 4. (Left) Photograph of front end electronics PCB's**. Figure 5. (Right)** Photograph of processing electronics.

5. Electronics Engineering Group's contribution to outreach programmes of the Institute

EEG has always been participating actively in educating school children and college students on several occasions via the i) Institute's open day celebration which happen twice a year ii) visiting student programme(VSP) – an opportunity created by the Raman Research Institute for the students to take part in the on-going research activities of the Institute and get hands-on experience in both theoretical and practical aspects of research, iii) while students do their project work in the laboratory as part of their academic curriculum and iv) during visits by college and school students in and around Bengaluru and elsewhere in the country. Following are some of the pictures showing EEG staff members interacting with school and college students during the open day celebration.

Figure 6. EEG staff members interacting with students during the Open day celebration

As part of outreach programme, one of the M.Tech students working with EEG designed and developed an octave bandwidth dipole antenna in the frequency range 2-4 GHz for the APSERa (Array of Precision Spectrometers for the Epoch of Recombination) project which aims to detect very faint spectral features at the recombination frequencies in the spectrum of the Cosmic microwave background radiation. The antenna is frequency independent having i) single primary lobe ii) achromatic radiation patterns iii) spectrally smooth return loss characteristics (few parts in 10^5) iv) very low sensitivity to man-made radio frequency interference and v) very low noise pick up through its backlobes. Development of a Log spiral shaped reflector has been the novelty in this design to achieve most of the desired characteristics. The prototype dipole antenna fabricated for validating its functionality is shown in Figures 7-10 along with its electrical characteristics.

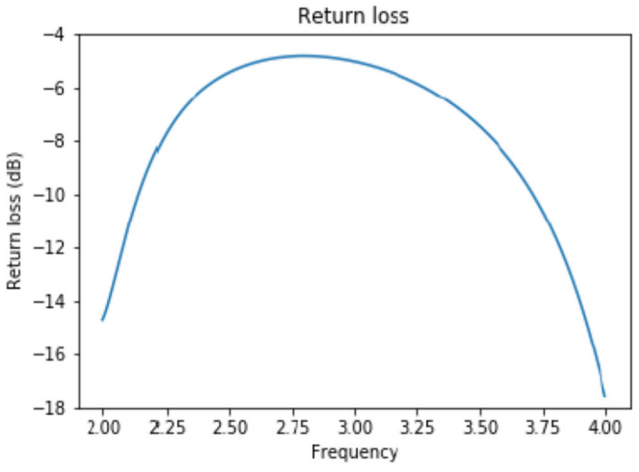


Figure 7. (Left) Log-spiral reflector based octave bandwidth frequency independent dipole antenna **Figure 8. (Right)** Spectrally smooth return loss characteristics of the antenna.

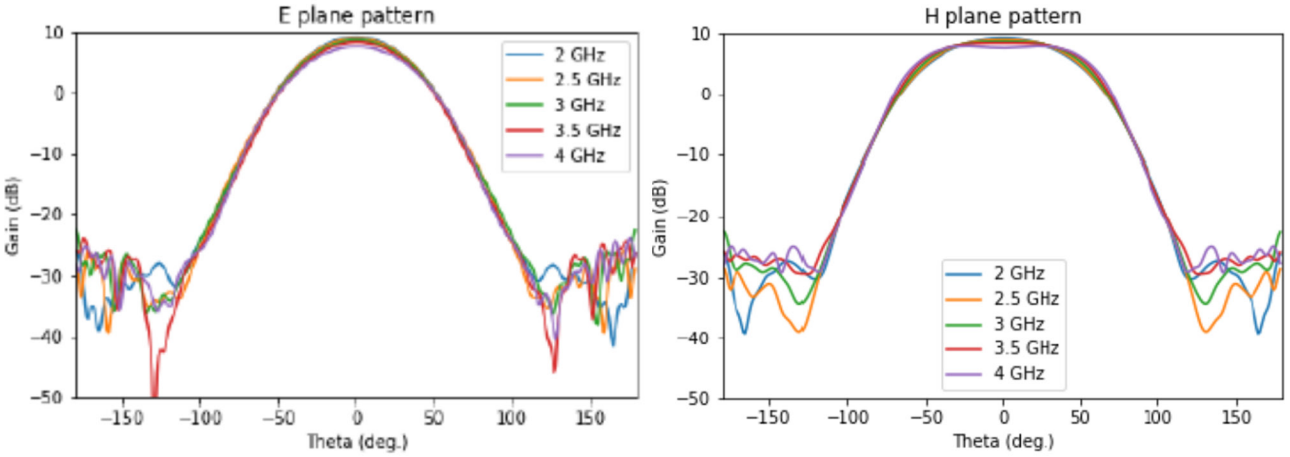


Figure 9. (Left) Frequency independent E-Plane patterns of the antenna. **Figure 10. (Right)** Frequency independent H-Plane patterns of the antenna.

Mechanical Engineering Services

The Mechanical Engineering Services (MES) provides mechanical design, prototyping and fabrication facilities to various departments of the Institute ranging from preliminary design concepts to final stage fabrication of various components, equipment and experimental setups. MES also provides mechanical assistance to various labs as well as overall infrastructure development of the campus and its facilities. MES mainly consists of a basement workshop with multiple machines including a CNC

Left panel from top: trolley with rotary base and an aluminium tray to hold electronics for the X-ray polarimeter (POLIX) being built at RRI and Teflon anode bush for use in X-ray lab. **Right panel from top:** Pyramidal horn antenna, electronic chassis fabricated for EEG and brass clamp for holding optical posts. Bottom panel: clamps for holding optical posts.

machine, a sheet metal workshop, a painting section and a carpentry section. MES also has licensed software such as CATIA-V5, Autodesk product design Suite, Creo 2.0, CamWorks etc. in order to help with design and simulation work for numerous projects and experimental setups.

Below is a brief description of activities undertaken by MES during 2019-20.

Using stainless steel tubing, fabricated a hoisting structure for loading the X-ray Polarimeter (POLIX) payload on to the PIM deck (a honey comb structure which will hold the payload). Holes were provided at the base of the structure for attaching the payload while the top is fitted with four eyebolts for lifting.

A trolley was fabricated with a rotary base which can be locked at any given angle for access to payload during testing and transportation. Fabricated, using the CNC machine, an aluminium tray to house the electronic components of POLIX. The trays were customized to fit the components snugly in their respective slots.

Teflon anode bush were fabricated at MES for use in the X-ray astronomy lab.

Fabricated a pyramidal horn antenna to required specifications. A brass screw rod attached to an aluminium plate allows for up and down motion of the plate thereby changing the volume enclosed by the pyramid horn, enabling data collection at a range of radio wavelengths.

Fabricated variety of clamps using aluminium and brass for use by members of the LAMP group as well as a electronic chassis for the Electronics and Engineering group. Pictures of components fabricated by MES is shown above.

Library

The RRI Library founded by Sir C V Raman in 1948, started functioning with his personal collection of books and journals. This library has both print and electronic information resources. The library is central to all the research activities and science communication of the Institute. Library caters to both general and specialized information needs of its users. Currently, the library has a total collection of 70897 comprising of books and bound volumes of journals. Out of this, 29276 are books and 41621 are bound volumes of journals. During the past year the library subscribed to 24 e-journals, 50 print journals and arxiv. Library has a total of 670 non-book materials. Grammarly software to aid writing skills was also added to the collection.

Library activities during 2019-20

Renewed partnership of RRI Library with National Knowledge Resource Consortium for next three years from 2019 has brought in online access to 4600 journals published by 15 publishers. RRI library is a content partner to the National Digital Library of India project of IIT Kharagpur. Research output of RRI is hosted on https://ndl.iitkgp.ac.in/, which acts as a single window to the nation's scholarship. Library web page is continuously monitored to keep it current and provide access to both subscribed and open source content of research interest. Plagiarism check of 9 theses submitted for the award of the doctoral degree was done at the library in addition to 24 research papers and few dissertations. ResearcherID of the entire faculty was updated regularly. Article processing charges of 11 papers were handled by RRI library. Partnering with Gubbi Labs, a social media centre, resulted in one research result of RRI appearing as news items in popular dailies during 2019-20. RRI library plays a role in outreach activity by donating Hindi books to various school libraries. Library working hours was extended from 6 PM to 10 PM in June 2019.

Library automation and Digital Library

The library has migrated totally to KOHA – open source software. The functions of the software is constantly getting improvised with more facilities and features enabling better services. All the KOHA related activities were done in-house.

The Raman Research Institute Digital Repository also known as e-Sangrah is an active repository of variety of information related to the Institute. The digital repository is currently hosted on version 6.0 of DSpace. Scholarly publications are uploaded regularly. Digitization of archival materials, photographs, and audio/video continued during the past year. Thesis submitted to RRI was also uploaded to the repository. Number of uploads during 2019-20 were 419. The total records on RRI Digital Repository currently stands at 10649. "Imprints-collection", an off shoot of RRI digital repository continues to thrive with regular updated information. This bio-bibliographic database currently has 30 profiles of superannuated scientists and 5 profiles of those scientists who have left RRI to pursue assignments elsewhere and have left behind some imprint in the form of publications with RRI affiliation. During National Science day celebrations on 28th February 2020, the library had organized the display Sir C V Raman's photographs and narratives to depict his life and science.

Training activity

RRI library has kept up the tradition of supporting manpower development programs by giving internship training to students of Bangalore University, Bengaluru; Kuvempu University, Shimoga; Shri Jayachamarajendra Government Polytechnic for Women, Bengaluru. During the past year, 10 students from these library schools were trained.

Other Events

1. Events such as author workshop, training programs to use information products were conducted.
2. Inauguration of National Library Week was held on 14th November at RRI library. Prof Madhusudana gave an invited talk on "RRI Science Museum - Raman's collection of Crystals and Musical Instruments".
3. Library had theme display of books on the occasion of Republic day. Additionally a book exhibition was also organized during this year.

Computer Group

The Computer group manages and maintains the IT infrastructure in the Institute and handles and supports various computing needs of the research groups and other departments. The computer group undertook a few activities apart from the routine work. Open Source softwares were used to create Wiki and file repository for documentation and for the PRATUSH project; created and published online forms for recruitment for various positions; set up and hosted a VPN server and DNS servers with latest version of OS and softwares. Bitdefender Anti-virus with centralized management console was procured and installed in all the computers/laptops in the campus.

There was a need for a better and enhanced High Performance Cluster(HPC) for computing. A tender for HPC with the suitable and latest processor and configuration was published. The bids were received and evaluated and financial bid was opened. The purchase order for the same has been placed and we will be getting the 1024 cores HPC soon.

The point-to-point 2Mbps link from the Radio Observatory in Gauribidanur to RRI was upgraded to 4Mbps; which acts as a backup link. One of the rooms in the Library was Audio-Video enabled by the installation of a short-throw projector, motorised screen and speakers. A 150" motorised 16:10 wide projector screen was procured and installed in the Auditorium which replaced the 100" motorised 4:3 projector screen.

The installation and commissioning of the 120KVA modular UPS was completed and the new Data Center is ready for use. All the servers and network equipments will soon be moved to the Data Center.

Knowledge Communication

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 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 scientific staff and other students encourages the students to not only think for themselves but also critically question others. A regular exchange of ideas and knowledge promotes an open-minded approach towards science and a willingness to learn which is, as acknowledged everywhere, extremely important for success in the academic arena. Apart from the academic members within the Institute itself, graduate students under the PhD programme are also exposed to the larger and more diverse scientific community through attendance of relevant national and international conferences and workshops where they get a perspective on a bigger picture in their field of research.

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

During 2019-20, 105 students from all over India were enrolled in the PhD programme and conducted research with scientific staff members from the four broad research groups at the Institute.

During the year ten PhD theses were completed and submitted for review:

S.N	Name	Thesis Title
1	Meera Thomas	Surfactant-Polyelectrolyte Complexes: Structure and Interactions
2	Raste Janakee Dhirajlal (JAP)	Analytical Formalism to Study the 21cm Signal from Cosmic Dawn and Epoch of Reionization
3	Raj Prince	Multi-wavelength Data Analysis and Theoretical Modeling of Blazar Flares
4	Simanraj Sadana	A Fresh Look at Classical Theory of Light with Applications to Quantum Interferometry
5	Varun	Understanding the Magnetic Field Configuration in X-ray Pulsars through Spectroscopy and polarimetry
6	Sushil Dubey	Mechanical Responses of Neuronal Cells and Spider Silk
7	Swamynathan K	Synthesis and Characterization of Some Discotic Amphiphiles
8	Ashutosh Singh	Creation, characterization, and manipulation of quantum entanglement in a photonic system
9	Sanjay Kumar Behera	An Experimental Study of the Kinetically Arrested States of Colloidal Suspensions
10	Santanu Das	Non-equilibrium behaviour in self-driven systems

Seven PhD theses were awarded:

S.N	Name	Thesis Title
1	Segireddy Anirudh Reddy	Quantum Measurement and Cloning of States
2	Deepak Gupta	Fluctuations and large deviations in non-equilibrium systems
3	Nafisa Aftab	Orbital Temporal and Spectral Properties of X-ray Binaries
4	Madhukar S	Influence of some sterols and nucleotides on the structure of self-assembled amphiphilic systems
5	Kumar Shivam	Geometry and Physics of Entanglement
6	Aswathanarayana Gowda M.	Synthesis and Characterisation of Some Novel Banana and Discotic Liquid Crystals
7	Venkata Jagadeesh Rachuri	Electrochemical Studies on Functionalised Indium Tin Oxide (ITO) and Graphite Oxide (GO) Surfaces

Postdoctoral Fellowship Programme

RRI offers a postdoctoral fellowship programme, which is open for applications through the year. This fellowship is initially offered for a period of two years and usually extended to three, following review. Postdoctoral fellows are expected to work independently and have complete academic freedom in the sense that they can choose their own research problem and collaborator. It is not mandatory that a postdoctoral fellow works under the purview of any of the four broad research groups at RRI either or is attached to a specific scientific staff 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. A healthy amount of mutually beneficial interaction with the scientific staff is desired so that collaborations can be struck up. Also participation of the Fellows in the academic activities of the Institute and student supervision as co-guides is encouraged even though there are no teaching responsibilities.

Candidates who have at least one year of experience as a postdoctoral 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 2+1 years. Further details about the Postdoctoral and Pancharatnam Fellowships can be found on the RRI website.

During the year 2019-20 there were 19 Postdoctoral and Pancharatnam Fellows at RRI.

Research Assistants Programme

This Programme provides opportunities for graduates (BSc/BE/BTech) and post-graduates (MSc/MTech) to participate in the research of the Institute and assist in the research by joining our research staff in one of the professional research works. These opportunities arise when research activity requires specialized help that is technical, computational or analysis and cannot be done by the scientific and technical members of the Research Facilities of the Institute. Research Assistants are for when research activity requires specialized assistance in the research work, which may be for durations up to 2 years. The specialized assistance may include engineering and computational skills that are either not currently available in the Electronics, Computing and Mechanical engineering groups of the Institute, or where the quantum of work required at that instance overwhelms the resources of the Institute. The participation is intended to motivate the Research Assistant to pursue careers in research, research support, develop technical skills particularly in hands-on experimental methods and move on to higher learning empowered by the in-house experience.

During the year of this report, 31 personnel were involved in research activities via the Research Assistants programme.

Visiting Student Programme (VSP)

The Programme is aimed at offering research experience to highly motivated students who are presently pursuing their Undergraduate or Masters Studies or who are in a gap year that is within a year of their completion of these degrees. Exceptional high school students may also be accepted as interns under this scheme. The purpose of the programme is to expose these students to the research of the Institute and motivate them to take up research as a career. Research Staff at RRI accept VSP students so that significant numbers of Undergraduate and Masters students are given an experience of experimental, phenomenological and theoretical physics/astronomy and thereby gain motivation to enter into research careers. In particular, experimental laboratories at RRI provide students the opportunity to participate in activities that invent, design, develop, build, and commission complex systems that explore frontier areas in the physical sciences, together with learning theoretical tools necessary to understand the complex systems and their purposeful design for the science goals. Enrollment to the Visiting Student Programme is open throughout the year.

Undergraduate and postgraduate students currently enrolled in Universities may undertake their research credits at RRI by working with a research staff member in a research project of the Institute as a separate part of the VSP scheme.

During the year 2019-20, 89 students availed of this programme. A complete list of VSP students who interned at the Institute during the year is given in Appendix VI.

Academic Activities

Conferences

Institute members visit various other institutions in India as well as overseas 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. Last year, scientific staffs and students of the Institute attended numerous conferences in India, Austria, Belgium, Canada, China, France, Germany, Italy, Mexico, Netherlands, Poland, Serbia, Slovenia, Spain Switzerland, UK and USA.

In addition, scientific staff 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 research being done on specific research topics. They are delivered by visiting 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 an 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. The colloquium aims to cover emerging 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 India and the world to deliver the seminars and colloquia. A complete list of speakers and the diverse topics presented is given in Appendix III.

Visiting Scholars

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 104 scholars who visited RRI from both Indian and international institutions. RRI is happy to have hosted so many academic visitors and thanks all of them for contributing to the wonderful diversity and dynamism of the research atmosphere at the Institute.

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

Science Forum

Owing to the very large number of papers that are published annually, these days it is nearly impossible for a scientist to stay abreast of the research going on outside his or her areas of specialization. To partially remedy this situation, the RRI Science Forum was conceptualized and first came into being in 2014. The goal was to provide an attractive forum to all scientific members on campus for discussions on current research in a variety of topics. Gautam Soni, Andal Narayanan and Nayantara Gupta are the organizers of this regular event. The RRI Science Forum is held on alternate 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 scientific staff member or postdoctoral fellow) followed by the "Science Talk" (where the chosen paper is presented by a PhD student).

Typically, as part of the RRI Science Forum, 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. Through the year 2019-20, the forum has become a useful platform to learn about and appreciate the breadth of research done in RRI.

A list of publications reviewed during the RRI Science Forum meetings last year is attached to the Annual Report as Appendix V.

Extramural Activities

RRI engages with the wider society for communications on science and related topics. RRI staff and students routinely organize and participate in popular seminars, talks, workshops and outreach events conducted by the GoI. RRI also invites and welcomes school and college students to visit the campus and interact with scientific staff of the Institute. Apart from these general interactions, over the years many college students have gained hands-on experience working with sophisticated Radio Telescopes at the Gauribidanur field station. Additionally, RRI shares its latest research, events, activities and general news through Facebook, Twitter, blogsposts, YouTube and Newsletters. Once every two years, RRI coordinates the selection and participation of Indian high school students in the International Science School held in Sydney, Australia. All of these continued in 2019-20 with participation in a variety of outreach activities. A comprehensive list of RRI member outreach activities in the form of popular talks, seminars and workshops is given in Appendix II. Other major outreach activities are discussed below.

RRI facilitates talented Indian high school students' participation in the 2019 Sydney International Science School

The fortieth Professor Harry Messel International Science School (ISS) 2019, organised by the Physics Foundation of the University of Sydney was held between 7th and 20th July, 2019. A total of 126 students from Australia, China, Japan, India, New Zealand, Thailand, UK and USA were awarded the scholarships for 2019. Raman Research Institute coordinated the selection of students from across India and facilitated their participation in the two-week program. Yashasvi Ghadale, Lakshika Rathi, Stuti Khandwala, Ayushman Tripathy and Angikar Ghoshal participated in the Science School.

The theme for ISS 2019 was Frontier science, and the lectures were all based on cutting edge scientific research being pursued around the world. The enlightening and interactive talks by eminent researchers were the highlight of the program. The lectures covered a vast array of fantastic science topics including the standard model of particle physics, quantum computing, genomics, astronomy, machine learning, climate change, ethics in science and psychology. Alongside the lectures we also attended hands-on lab sessions and were also engaged in a plethora of fun activities ranging from hands-on DNA extraction, infrared and nuclear magnetic resonance spectroscopy, to playing fun games and figuring out the math behind them and even dancing with virtual reality programs. The team had also organised museum visits, a cruise party and a DJ night!

The fifteen days spent as a part of ISS has truly been an enriching and eye-opening experience. The participants also had the privilege of getting their questions answered by leading scientists during the question answer sessions after the talks. Also, this being an International program, presented an opportunity to mingle with people from around the world. In a nutshell, the International Science School has been an inspiring experience and has enabled the participants to gain a wider perspective about science.

A group photo of the participants at ISS 2019

Activities at the Gauribidanur field station

The Gauribidanur field station continues to be a hub for student interactions and training. School and college students are invited to visit the field station and workshops are frequently organised. Two workshops imparting hands-on experience in radio astronomy are offered every year to interested students. One is the Camp for hands-on training in radio astronomy organized jointly with the Indian Institute of Astrophysics every summer while the other is the hands-on experience program with the Sky Watch Array Network (SWAN) organized by Avinash Deshpande (AA) twice a year. Below is a brief description of the programs that took place at the field station during the past six months.

Workshop on Geometry and optics

An experiential learning workshop on Geometry and optics was held at the field station for a group of nine higher secondary students from The Houde Academy, Shenzhen, China on May 7-9 and May 13, 2019. This is the second such visit of students from China to this workshop.

Camp for hands-on experience in radio astronomy (CHERA)

Camp for hands-on experience in radio astronomy (CHERA) was held in collaboration with IIA again this summer for a group of thirteen undergraduate students. The students were from various institutions all over India. The school was held from 21st June to 7th July. The students were introduced to basics of radio astronomy and were given practical training on using radio telescopes for observations. For example, they used the 12-m radio telescope at the station and obtained 21-cm spectra from many Galactic longitudes, which were used to construct the rotation curve of the Milky Way.

SWAN-CHERA Summer 2019

In our continued effort to provide due opportunity to undergraduate and post-graduate students interested in SWAN, visits of about twenty students to Gauribidanur field station were facilitated in four batches this summer between 11-17 June, 9-15 July, 16-22 July and 23-30 July. As on previous such occasions, each of their one-week stay provided them a setting to learn about radio astronomy techniques in general, and the SWAN Phase-0 (8-station) system in particular, as well as providing opportunity to operate the system in an uninhibited manner, and conduct tests/observations in single station and interferometric modes. With this exposure and hands-on experience, the students were encouraged to follow up their interest in using the system via remote access. The participating students were all affiliated to various institutions including IITs, IISERs, NITs and universities.

Participants from the summer camp for hands-on experience in radio astronomy with the 12-m radio telescope as a background. The camp included a lecture by Ravi Subrahmanyan (AA).

RRI at the India International Science Festival, 2019

The fifth edition of the India International Science Festival (IISF, 2019) jointly organised by the Ministry of Science and Technology and Ministry of Earth Science and Vijnana Bharati was held in Kolkata between 5th and 8th November 2019. RRI has been participating in this mega event every year since 2016 by setting up pavilions that showcases the current research areas and research highlights from the past year. The 2019 pavilion displayed panels, audio/video content, live demonstrations as well as models of radio and X-ray telescopes, antenna and detectors. RRI members Sachidanand Barik and Sandeep K represented the Institute and interacted with the visitors.

The pavilion displayed a nice blend of panels on: the Institute, its PhD, postdoctoral, visiting student program, research assistant program and current research activities along with overview panels on the four research groups on campus. The research activities panels discussed: the objective behind the design and development of the Sky Watch Array Network and how interested students can gain hands-on experience right from the design stage to research using the array network; a RRI-built precision radiometer SARAS 3 to study the early universe when the first stars formed; a novel cross-telescope built for high frequency (7-11GHz) spectral-line continuum studies of star formation in the galactic plane; how the nanoscale biophysics lab members are using in-house built nanopores to study shapes at the nanoscale; the cell biophysics lab's efforts in using in-house built Micro-extension rheometer to study the effects of mechanical deformations in axons; the Ultrafast and nonlinear optics lab efforts towards generating laser-produced plasmas and using them for elemental analysis of materials of unknown composition; recent demonstration of high precision magnetometry using spin noise measurements and non-perturbative detection of atomic population in different hyperfine states. A live demonstration on very low Reynolds number laminar flow was also part of the pavilion. Over the four days many school and college students visited RRI's pavilion. IISF served as a platform for meaningful interactions and exchange of ideas between RRI representatives and the wider society.

The RRI pavilion at IISF 2019. **(Bottom)** RRI members interacting with the visitors.

RRI's participation in the Square Kilometer Array (SKA) week

Students and staff of our institute participated in a major Radio Astronomy and Engineering outreach event, the SKA-Week organized by the Department of Science and Technology (DST), Department of Atomic Energy (DAE) and the National Council of Science Museums (NCSM) along with several other participating academic institutions and industries. The event was part of a mega science event the Vigyan Samagam, and it was held as a moving exhibition across the Indian cities: Mumbai, Bangalore, Kolkata and New Delhi. The aim of this effort was to introduce and create interest in the fields of Science and Engineering among the public and student visitors. The Bangalore leg of Vigyan Samagam was held at the Visvesvaraya Industrial and Technological Museum (VITM) between 29th July to 28th September, 2019. RRI along with other Institutions participated in organising an SKA stall for public viewing over the entire duration of the exhibition and in conducting special radio astronomy and engineering talk sessions over the SKA-week between 10 - 14 September 2019. Astronomy and Astrophysics student members Aditi Vijayan, Akash Kumar Patwa, Ashwin Devaraj, EEG staff members Raghavendra Rao K B, Mugundhan V and postdoctoral fellows Anjan Kumar Sarkar, Kshitija Kelkar and Narendra Nath Patra volunteered for the various events. Public science lectures were given by AA members N Udayashankar and A A Deshpande. The engineering lectures were delivered by Srivani K S, Girish B S, Mugundhan V, Somashekar R and Ragunathan A. We also had our former colleague Rajaram Nityananda delivering the first day radio astronomy lectures. Besides our RRI staff, we had students and faculties from National Center for Radio Astronomy (NCRA), Indian Institute of Astrophysics (IIA), Indian Institute of Science (IISc), Birla Institute of Technology and Science (BITS-Goa), NCSM Mumbai and from various other educational institutes participated in the critical planning and execution of the event. This event attracted many participants, and a total of about 1200 students attended the SKA week events.

SKA will be an array of telescopes, spread over hundreds of kilometres, in two different continents. In the first phase there will be about 200 dishes in South Africa's Karoo region, and over 130,000 low frequency antennas in Western Australia's Murchison Shire (MRO), that will monitor the sky in unprecedented detail, in a complementary range of radio frequencies. SKA will complement the great observatories being built in other wavelengths. The SKA will use interferometry concepts to combine a very large number of antennas in order to make very sensitive measurements of weak cosmic signals.

A total of 13 countries including India are currently funding the SKA while around 100 organisations in about 20 countries representing over 1,000 scientists and engineers are participating in its design and development. RRI is involved in the design of critical signal processing components for the telescope. SKA will play a major role in radio astronomy for decades to come and when completed will be the largest Radio Telescope on Earth.

A collage of images from SKA week

Student visits to RRI campus

The Institute routinely arranges student visits to the campus. The visits usually include an informal interaction session with a research staff in the RRI auditorium. Visits to some of the labs on campus were included as part of the program; these were to learn about some of the current research activities at RRI and the "lab-setting" that enables the research. Combined with the ever popular guided tour of the RRI museum the visits not only give the students glimpses into present and past scientific research activities in a visually impacting manner but also a direct connect with scientists and PhD students at the institute. Between April 1, 2019 and March 31, 2020 around thousand students visited RRI. A brief description of the visits is given below.

On 24th April, thirty students from electronics engineering department of Sri M Visvesvaraya Institute of Technology, Bangalore visited the labs in electronics engineering group. During the visit the students interacted with A Raghunathan (EEG) and other members of EEG. The visit concluded with Sasikumar giving a guided tour of the RRI museum. On 2nd May six meritorious students, through the Aryabhat foundation, (Gwalior, MP), an organization that seeks to promote basic science among young students, visited RRI. These students were the best performers of state level Aryabhat astronomy quiz 2018-19. K S Dwarakanath (AA) interacted with the students. This was followed by a visit to the Cosmological recombination and reionization lab. Jishnu Nambissan (AA) interacted with the students and explained the current ongoing research activities in the lab. The visit concluded with a guided tour of the RRI museum. Thirty high school students visited the RRI museum on 3rd May as part of a summer course conducted for them by the J N Planetarium, Bangalore. On 8th May, thirty students and four faculty members from Indian Academy Degree College, Bengaluru visited RRI. Udayashankar (AA) interacted with the students in the auditorium. This was followed by a visit to Andal Narayanan's Quantum optics lab and a guided tour of the RRI museum. Thirty-seven students from Jagadis Bose National Science Talent Search visited RRI. The students had an interaction session with Joseph Samuel (TP) in the RRI auditorium followed by visits to EEG labs. The visit concluded with a guided tour of the RRI museum. On 24th July thirty-five students aged between 12-13 years from Cambridge International School visited the RRI museum. On July 31, fifteen students from St. Josephs Boys school visited RRI. The visit started with an interaction session with K S Dwarakanath in the RRI auditorium followed by visits to the EEG labs and a guided tour of the RRI museum. On August 7th, twenty-six students and two teachers from Chinmaya International Residential School, Coimbatore visited RRI. Joseph Samuel (TP) interacted with the students on black holes and its recent imaging using the event horizon telescope. This was followed by visits to Sayantan Majumdar's Soft and adaptive materials lab and Sandeep Kumar's Chemistry lab and the RRI museum. As part of their curriculum one hundred and twenty students from Manipal School of Architecture and Planning, Manipal Academy of Higher Education visited RRI in three batches of forty students each on the 8th and 9th of August and performed a documentation study of the library and other building on RRI campus. G B Suresh (E&B) assisted the visiting students in this study. The next visit during this period was on 23rd August when thirty students from the department of electronics and communication engineering, New Horizon College of Engineering, Bangalore visited RRI. Following an interaction session with Udayashankar (AA) in the RRI auditorium the students visited the EEG labs and the RRI museum. The next visit was on Founder's Day (November 7th) when around thirty students and three teachers from Parikrma Foundation, thirty-six students and eight teachers from Presidency School and fifty students and three staff from Kautilya Vidyalaya visited RRI as part of the founders Day celebrations. The second visit was on November 27th when twenty-eight students and accompanying staff from the National Center for Learning visited RRI. The visit started off with an interaction session with Andal Narayanan (LAMP) on the topic "The Quantum Light: From an engineering perspective". This was followed by a visit to the Raman museum. The days' agenda concluded with visits to the Quantum Optics lab, Ultrafast and Nonlinear optics lab and the Quantum Mixtures lab. On December 18th, thirty students and three staff from Ananda Vidyaniketan visited RRI. Udayashankar N (AA) interacted with the students in the RRI auditorium. This was followed by visits to the electronics engineering group labs and Raman Museum. Twentyfive MSc Chemistry students from St. Aloysius College visited RRI on 9th January. During their time at RRI they visited the chemistry and SCM lab facilities. They also visited the Raman museum. Around hundred students and staff from schools in various talukas of Karnataka visited RRI on January 31st under the Vijyana Darshana programme. This is program organised by the Karnataka State council for Science and Technology with support from the Department of Science and Technology, Government of India. K S Dwarakanath (AA) interacted with the students on the topic Earth: Size, Shape and order of magnitude estimates. The interaction session was followed by a visit to the Raman museum. Seventy students from Mahila Seva Samaja visited RRI on February 5th. The students had an interactive session on Eclipses with Supurna Sinha (TP) followed by a visit to the Raman Museum. The final visit during this period was on National Science Day when 30 students each from Govt. Girls High School, Malleshwaram, Sri Vidya Mandir, Poornaprajna High School, Kendriya Vidhyalaya, Govt.

High School, Malleshwaram, Kishore Kendra, Himanshu Jyothi Kala Peeta, Nagasena School, National Public School, Rajajinagar, Stella Mary's Girls Convent School, New Horizon College and general public visited RRI as part of the Open Day celebrations.

Collage of images during student visits to RRI

RRI in the media

The professional pursuit of science may be a relatively personal enterprise, or a joint activity of a few scientists collaborating with each other towards a common goal, or an enterprise involving hundreds and even thousands of scientists who may be distributed worldwide. Any insight gained or phenomena discovered are then communicated in the form of publications that are intended mainly for fellow scientists. On the other end of the spectrum is the general public whose money more often than not enables these scientific pursuits, but are none the wiser for it. Human beings have this innate curiosity to know and understand the natural world they live in and it would ultimately serve science well to kindle this curiosity, particularly in impressionable young minds. Whatever be the reason, communication of "hi-fi" scientific research couched in language that is easily understandable to one and all is highly desired. Additionally, these popular science articles, snippets and news may be disseminated in such a way as to have maximum outreach. The Raman Research Institute is attempting to bridge this gap by posting general write-ups based on research publications by RRI research staffs and students on Facebook, Twitter and blogposts. During 2017-18, RRI continued its commitment to research communication by launching the official RRI YouTube channel. The channel playlists contain lectures, talks, workshops, student and postdoc videos, and archival videos. Along with adding new playlists, existing playlists will be periodically updated with new videos. Between April 1st 2019 and March 31st 2020 there have been 34 facebook posts, 39 tweets and 7 blog posts. Many of our posts and tweets have been liked and retweeted by DST from their official Facebook and Twitter pages. We now have upwards

of 7486 people following us on Facebook and 3038 people on twitter reading and commenting on our posts. The RRI YouTube channel was launched on 16 March 2018. Since then the channel has grown to include 14 playlists with 141 videos that are open for public viewing.

To enable better outreach and communication of science, DST, DBT etc through Vigyan Prasar launched Vigyan Samachar, an official platform for dissemination of research from autonomous bodies. RRI actively shares its recent research with DST which are published in Vigyan Samachar's and DST's websites. Since the start of Vigyan Samachar in January 2020, fourteen stories have been prepared on RRI research. This has spawned multiple articles in news and print media. RRI science and events stories have appeared in all major newspapers like The Hindu, Times of India, Deccan Herald, Financial Times, Indian Express etc.. while their presence is online media is through Indus Dictum and Research Matters among others.

The biannual RRI Newsletter is another such endeavor that highlights recent research at the Institute through its science articles. The articles are written in a language that enables sharing the Institute's exciting research with the wider community. The Newsletter also serves the purpose of updating RRI members, collaborators and the general public on recent news and diverse activities that are part of daily functioning of the Institute. To enable easy access to all these posts, tweets, blogs, videos and newsletter a link "RRI in the media" has been created on the RRI homepage.

Official Language Activities

The Official Language (OL) Department of the Institute is committed towards promoting the use and implementation of Hindi in day-to-day official work. The main responsibility of the department is to create awareness of the OL Act and help the Institute achieve the targets as laid down in the Annual Programme issued by the Department of Official Language every year.

The following activities were undertaken during the year under report.

- General orders, Notices, Advertisement, Press releases / Notings, Contracts, Tender forms and Tender notices were brought out bilingually. Section 3(3) of the OL Act was fully complied with.
- Letters received in Hindi were replied to in Hindi.
- Hindi Version of the Institute's website was updated periodically.
- All forms and Standard Formats being used in the Institute were made bilingual.
- The Quarterly Progress Reports regarding progressive use of Hindi are being sent to the Ministry of Science and Technology, Regional Implementation Office and the Town Official Language Implementation Committee periodically.
- The Annual Report has been published both in English and Hindi versions.
- Hindi Fortnight was observed in September 2019 under which various competitions were organized for the staff. viz. Essay Writing, Quiz, Antakshari, Administrative Terminology, Crossword, and Recitation and Conversation.
- Hindi Divas Samaroh was celebrated in the Institute on 26th September, 2019. Shri Saurabh Mandal, Scientist E, Centre for Artificial Intelligence and Robotics, Bengaluru, was the chief guest of the occasion. He delivered an informative and useful talk on "Alternative means of communication during natural calamities".
- Hindi workshops were conducted periodically and Lectures were delivered by experts on (a) OL Phonetic typing and Voice typing (b) Communication during Natural Calamities (c) Link Language: Hindi or Hindustani and (d) Bilingual entries in Service Book during these workshops. In addition to this, Table workshops and Internal Inspections were conducted regularly for all the Departments.
- Meetings of the Official Language Implementation Committee were conducted periodically with Specific Agendas. Concrete actions on the decisions taken in the Meeting was ensured.
- The Institute actively participated in the Town official language implementation committee Meetings conducted during the year.
- Quote of the day and Word of the day in English with its Hindi equivalent were displayed daily on Bulletin boards across the Institute.
- Ten phrases in English with its Hindi equivalents were displayed on the Main Bulletin boards every month for use by officials.

Others

During 2019-20, RRI organized conferences, meetings and workshops described in detail under the section titled "Events". Other events include high teas on superannuation of regular staff, sports tournaments, concerts and a variety of cultural programs, both with invited performers and RRI members themselves.

Events

In-house meeting, 2019

The RRI In-house meeting is an annual event that aims to bring together the members of the institute engaged in research and related activities in the different research groups to share their scientific work. This year's meeting was held between 3rd and 5th April. As is the tradition, this event was organised by third year doctoral students. This program aims to provide a forum where students and faculties not only exchange ideas within their group but also with other groups. This meeting has been successful in achieving this goal.

There was active participation from RRI members resulting in 34 talks, each of 20 minutes duration and 23 poster presentations showcasing the diverse research activities across the Institute. The meeting also included some live experiment demonstrations of the Institute's research. On all three days the sessions started at 9:30 in the morning with discussions continuing late into the evening. The final session of the in-house meeting saw enthusiastic participation in the open house discussion, a session that allows all members of RRI to discuss and point out the problems they are facing in their academic as well as other aspects of their life at RRI. Some of the topics of the discussion were the need for a dedicated computational facility at RRI, better infrastructure and living spaces in the hostels to cater to the growing student population as well as discussions about best practices for healthy and hygenic food in the canteen. The in-house meeting also included a scientific quiz competition, photography competition and merchandise design competition. The meeting concluded with a vibrant cultural evening followed by a gala dinner.

(Top) During one of the in-house talks in the RRI auditorium, **(Bottom)** during the cultural evening

RRI special lectures

Lecture 1: Mind and the Universe

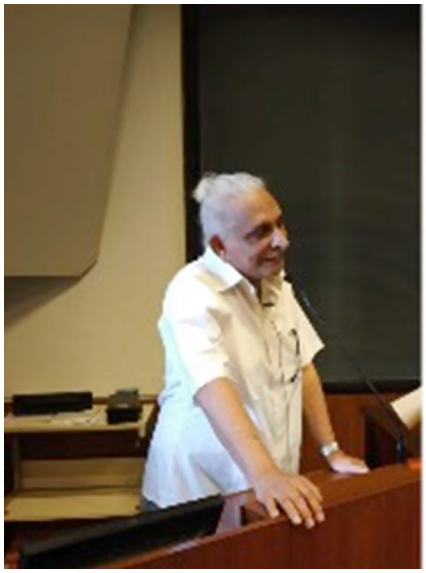
Sri M, a renowned spiritual guide, social reformer and educationist delivered a talk titled "Mind and the Universe" on 26thApril in the RRI auditorium. Sri M is the founder of The Satsang Foundation, which currently runs many social initiatives in the areas of education, health and environment in Andhra Pradesh, NCR, etc. His message seeks to transcend the outer-shell of all religions, by exploring their mystical core to nurture the innate goodness in every human being. To listen to this lecture visit https://www.youtube.com/watch?v=6yUcVlsr9Fg

Lecture 2: Language Diversity, Aphasia and the Future

Prof Ganesh Devy is a renowned scholar, cultural activist and a self-trained linguist. He played a key role in the People's Linguistic Survey of India, a mammoth undertaking launched to update knowledge about the spoken languages of India. He has promoted and published literature in twenty-six languages, opening the doors to education for many from our country's indigenous communities. He visited RRI on 22nd October, 2019 and delivered a lecture titled "Language Diversity, Aphasia and the Future". To listen to this lecture visit https://www.youtube.com/watch?v=szk_tGn1OVw

Lecture 3: Reflections on Ecology, Growth and Democracy in India

On the 8th of November, 2019 Shri Jairam Ramesh, a widely respected and popular voice in Indian politics delivered a special lecture titled "Reflections on Ecology, Growth and Democracy in India. He is currently a Member of Parliament representing Karnataka in the Rajya Sabha as well as the Chairperson of the Parliamentary Standing Committee on Science and Technology, Environment and Forests. To listen to this lecture visit https://www.youtube.com/watch?v=H__JqzXUVqU



Left: Sri M delivering his talk, **Right:** during the audience interaction after the talk

Left: Ganesh Devy(top) and Jairam Ramesh; **Right:** During the informal interaction session at the library

Founder's Day celebrations

The Institute celebrated Founder's Day (birthday of Sir C V Raman, November 7th) by inviting around 120 students from Presidency School and Parikrma Foundation, Bengaluru and Kautilya Vidyalaya, Mysuru to visit the Institute and interact with faculty and PhD students. The TP and SCM group had set up a number of interesting demonstrations in the coffee lounge area of the SCM building and the Chemistry lab, while the entrance space to the library was converted into a dark room for LAMP members to display laser based interference experiments. Visits to EEG included a guided tour of their labs and simple scientific demonstrations, while members of MES workshop gave the students live demonstrations of component fabrication using the CNC machine and lathe. The students were also given a guided tour of the Raman museum, while visits to the library gave the students a peek into Raman's life via a collage of photographs prepared by members of the Library. To facilitate better interactions and an immersive experience, the visiting students were split into smaller batches of 15 members and simultaneously escorted to the above locations by an able team of volunteers that included members from Administration. Lunch served as an informal setting where the visitors and RRI faculty discussed topics of common interest.

Conference on Quantum Frontiers and Fundamentals, 2020

Remarkable developments have occurred in recent times concerning investigations of fundamental aspects of Quantum Mechanics involving an intimate link between theoretical ideas and experimental studies, in particular, stemming from striking progress in the relevant implementation oriented technologies. Such developments include the coherent preparation and manipulation of quantum systems such as photons, electrons, neutrons, ions, and molecules. This, in turn, has given rise to a rich interplay between fundamental aspects of Quantum Mechanics, information theoretic studies and technologically relevant applications like quantum computing, quantum communication, quantum sensing and metrology, as well as other quantum-enabled technologies.

Against this backdrop, the second Quantum Frontiers and Fundamentals conference (QFF) was held at RRI between 13-18 January. The conference intended to bring together the relevant experimentalists and theorists for critically deliberating upon the state of play and prospects in developing further synergies between fundamental studies and frontier applications.

The conference objectives were twofold. Firstly, with most quantum information science conferences in India focussed towards theoretical approach based foundational developments, QFF 2020 aimed to bring together a synergy between fundamental studies and frontier applications, with equal weightage to both theoretical investigations and their experimental realizations. Secondly, with the rapid development of improved engineering techniques and fundamental approaches in secure quantum communication and computing, quantum-enabled technologies based on these progresses are becoming commercially available. In this light, QFF 2020 also intended to bridge the gap between academia and industry by enabling the sharing of latest research progresses and fostering collaboration opportunities between the fundamental experts and growing product-based initiatives in this field.

The major realization during the conference was the impact of quantum advantage over their classical counterparts, in the areas of secure quantum communication and other quantum-enabled technologies. More particularly, in a day dedicated to the discussion on the role of satellite-based approaches towards world-wide realization of quantum-enhanced communication security, it was pointed out by various international experts that the promotion and support of satellite-based efforts are crucial. The event helped in fostering further collaboration between various world-wide initiatives in this direction both among academia and industry.

The daily attendance in the conference was about 110 people. This majorly consisted of close to 40 invited speakers: national and international, 4 delegates from industries like Microsoft, Cambridge Quantum etc., 4 academic delegates from the University of Science and Technology of China, few delegates and honorary guests from ministries such as Department of Science and Technology, Ministry of Electronics and Information Technology etc. and government organization like Indian Space Research Organisation and about 55 contributory presentations/participations from other faculties and young researchers in the field of quantum information science. The conference also included a public lecture titled "Quantum Leap: From Test of Quantum Foundations to New Quantum Technologies" delivered by Professor Jian Wei Pan from the University of Science and Technology of China. Around 150 people attended this public lecture.

This conference was a second edition of the QFF series, which is currently a biennial event. With a significant growth in the number of foreign participants i.e. invited and contributory speakers, compared to that in QFF 2018, it was quite evident that the QFF series is gaining global importance as well as appreciation. The representation of

international experts was quite uniformly distributed from around the world. For the first time in an international conference on quantum information in India, besides academia, there was also a considerable participation from a few of the leading industries in this field. In this regard, it was recommended by the international and national experts as well as other dignitaries that this series continues to happen biennially and that it grows both in breadth and depth at each of its future edition.

(Top) Group picture of the conference participants in front of the RRI main building. **(Bottom left)** Urbasi Sinha in discussion with Professor Jian Wei Pan; **(Bottom right)** members of the Quantum Information and Computing lab at RRI who organised the conference along with delegated from the University of Science and Technology, China.

National Science Day celebrations

With an objective to promote science outreach among school children and the general public, the Raman Research Institute hosted an "Open Day" as part of its National Science Day (Feb 28th) celebrations. Students from various Government and private schools, colleges and general public visited the Institute during the day. Some of the schools and colleges from Bengaluru that visited include Govt. Girls High School, Sri Vidya Mandir, Poornaprajna High School, Kendriya Vidhyalaya, Govt. High School, Kishore Kendra, Himanshu Jyothi Kala Peeta, Nagasena School, National Public School, Stella Mary's Girls Convent, and New Horizon College.

A variety of demonstrations that explain basic science were conceptualized and executed by the PhD students and staff of the Institute. Members from the four research

groups as well as the facilities including Library, Mechanical Engineering Services (MES) and Electronics Engineering Group (EEG) were seen enthusiastically demonstrating experiments and interacting with the visitors. A peek into the experiments is given below.

A visitor to the "Dark Room" of the Light and Matter Physics (LAMP) group would witness a range of experiments that explain fundamental concepts in light-matter interaction. A sugar solution with a concentration gradient was used to bend light and motivate questions on refraction and the role of refractive index of a medium, while in another experiment the sugar solution served as a polarizing medium, bringing to light concepts such as polarization. The narrow slit at the center of a common shaving razor along with a laser pointer was used to recreate the famous Young's Double Slit experiment. Two different types of pin hole camera were built and used for creating images. Part of a glass rod that was immersed into a solution in a beaker magically disappeared; turns out this was due to the fact that the refractive indices of the rod and the liquid were similar.

The Astronomy and Astrophysics (AA) group used the simple concept of parallax to demonstrate a technique for measuring distances to many stars we see in the night sky. Using this technique, the visiting students enthusiastically measured the distance to an object. The students were pleasantly surprised to see that the value they measured using this technique matched reasonably well with the actual distance! Another attraction in the Astronomy and Astrophysics stall was the models of various telescopes used in Radio, X-ray and Optical astronomy. Students appreciated the fact that one can "see" the sky not only through visible light but also through X-rays, radio waves, gamma rays etc.

The concept of rotational inertia was explored using a set of weights and a rotating chair. The willing student volunteer sitting on the chair found out that the speed of his rotation is dependent on how he holds the weight. A compact fluorescent lamp (CFL), when taken close to a ball of aluminium mysteriously lighted up! What is going on? wondered the visitors. It was later revealed that a build-up of positive charge on the surface of the aluminium covered thermocol has caused the electrons in the CFL tube to impinge on the fluorescent coating at the lamp's surface resulting in light.

The Soft Condensed Matter (SCM) group members had a live demonstration of real time Fourier transform of sound and images. The historic and experimental importance of this technique was explained to the visitors. Mixing and unmixing of dye drops in a viscous liquid - a demonstration that visualizes the concept of very low Reynolds number laminar flow - was shown to the visitors. In another experiment the flow of a cross-linked polymeric solution into an open siphon was demonstrated. When a spinning rod was inserted into a solution, instead of being thrown outward as one would expect, the solution started climbing the rod - a demonstration of the Weissenberg effect for a non-Newtonian fluid. Corn starch suspension shows shear thinning and thickening behaviour with an increase in the applied shear rate. At lower shear rates it behaves like a viscoelastic fluid and at higher shear rates it behaves like a viscoelastic solid. These concepts were explained by asking the visitors to observe what happens when they punch hard on the surface of corn starch suspension as opposed to slowly inserting their hand into the surface. Instability of a cylindrical column of liquid is called pearling instability; it arises because of surface tension and explains many natural phenomena like why rain falls in the form of droplets, why we see dew drops on a spider web etc. The basic physics behind this was explained to eager visitors.

The Theoretical Physics (TP) group had designed simple demonstrations such as: using cylindrical glass bottles with water, grains and steel ball bearings to see how these affect rolling on an inclined plane, thereby motivating the concept of moment of inertia while an apparently anti-gravity toy was used to explain the concept of centre of mass. Water flowing through holes in a bottle mysteriously stops flowing when the bottle is dropped from a height. This was used to motivate the concept of gravity being nullified in a freely falling frame. A Mobius strip and its unusual topological properties was used to introduce and explain concepts in topology. A cube model with 720-degree rotational symmetry was used to introduce mathematical concepts like spinors. In all the demonstrations the students were encouraged to predict the outcome of the experiments. The related concepts were then explained to them with some mathematical details.

EEG had demonstrations on sensors, electronic filters and their applications and an interactive experiment where the visitor could know the frequency of their voice, while MES had live demonstration on fabricating components. The Library stall gave the visitors a peek into the life and science of Sir C V Raman through panels and newspaper articles.

The visitors also had the opportunity to interact with RRI PhD students and faculty regarding exciting science and technology initiatives and current research activities of the various labs of the Institute. The Raman Museum, which contains the personal effects of Sir C V Raman was also kept open for visits.

A collection of images from the National Science Day celebrations at RRI

Campus

The Institute campus is located in the northern part of Bengaluru. It covers an area of 20 acres replete with trees and shrubs. The hustle and bustle of the developing metropolis outside is left behind as one enters the Institute gates. The environment inside is a world apart: a campus that has landscaped greenery including a variety of species from near and far, patches of wilderness tended only by nature, together with the laboratories, workspaces and facilities. Distinctly a shade cooler, this sylvan setting is an attempt to create generative surroundings for the creative research and academic learning that goes on within the campus.

The campus hosts the buildings containing workspaces, laboratories, workshops, canteen, clinic and the guesthouse. And these are surrounded by aesthetically planned and well-kept vegetation that is very appropriate for a campus of a renowned research institute. Indeed, it was Professor Raman who had himself landscaped much of the campus. At the center of the campus lies the iconic main building, which faces a manicured lawn flanked on both sides by majestic eucalyptus trees that seem to reach for the sky. The lawn is where Professor Raman was cremated, respecting his wishes, and a Tabebuia donnell-smithii grows here as a memorial. The Institute is proud and obliged to respect and protect this special environment.

The campus abounds in flowering trees and shrubs like the common Hibiscus, Ixora, Frangipani, Gulmuhar, Golden shower tree, Bougainvillea and many more, indeed a welcome sight for the discerning. Members of the Institute and a lucky few elderly neighbors who visit the campus for an early morning constitutional are audience to nature's symphony. The sensitive ear might differentiate the cooing of the koel, chirping of the mynah and bulbuls and many more sounds whose origin is lost within the protective embrace of the branches and leaves. Looking up at the source of the screeching sound heard in the early afternoon, one might find a parrot dangling from a branch with one foot, the other foot holding what passes off for a delicacy in the parrot world, which it then proceeds to peck into and relish with gusto. Along with birds that are indigenous to this part of the country, migratory birds from North India and beyond wintering on RRI campus are a familiar sight. However, do not walk along the well laid out pathways trying to catch a glimpse of bird life, lest you step on - a snail lumbering along or the myriad armies of ants and other insect life that we share our campus with.

The Guesthouse on campus is equipped with rooms blending modernity with ethnic elegance 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 members of the Institute and also those who work at the Indian Academy of Sciences, which is also located in a corner of the campus. Informal meetings, 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, or on the terrace of the Library building that is in the canopy.

Minimal sports facilities exist in the limited open spaces on campus: there are spaces for Badminton, Volleyball, Table Tennis plus a small Football ground. The buildings adjacent to the Canteen houses a small Clinic where consultant medical practitioners pay visits at fixed hours on working days of the week, providing for the health and well-being of the members of the Institute and their families.

People at RRI

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M Gopinath

Jayamma – till 30.06.2019

C Lakshmamma

T Murali

Narayana

V Venkatesh

Ramanna

Varalakshmi

C Elumalai

A Ramanna

D Mahalinga

Mailarappa – till 29.02.2020

Marappa – till 31.07.2019

S Muniraju – till 31.1.2019

Rangalakshmi

D Krishna

T Mahadeva

C Sampath – till 31.08.2019

S Sridhar

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Matadeen, Security In-charge

Kiran Guddappa Hosalli, Consultant Security Supervisor (from 02.03.2020)

Hanumantha Raju SP, Consultant Security Supervisor (from 02.03.2020)

Belliappa AK, Consultant Security Supervisor (from 02.03.2020)

H Vaderappa – till 31.03.2020

BM Basavarajaiah

UA Earappa

H Gangaiah – till 31.07.2019

Keshavamurthy

Suresha

K Krishnappa – till 31.05.2019

K Pushparaj

OM Ramachandra

G Ramakrishna

M Sannaiah – till 31.10.2019

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M Balarama

CK Mohanan

G Prakash – till 13.08.2019

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G Raja

M Venkateshappa

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Shivamallu

Mangala Singh

Muniratna

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Dr. BV Sanjay Rao

Dr. PH Prasad

Dr. N Sundari

RRI Official Language Implementation Committee

Sharadamani, Consultant

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104. Synthesis/structural and mesomorphic properties of substituted hydrazide based calamitic molecules
Srinivasa, H.T.; Palakshamurthy, B.S.*; Mohammad, AbdulKarim-Talaq*; Venkatesha, M. A.*
Phase Transitions, 2019, Vol.92, p1043

105. New cyanopyridone-based unsymmetrical dyads: the effect of donor strength on their optoelectronic properties
Vinayakumara, D. R.*; Kesavan, Rajalakshmi*; Kumar, Sandeep; Adhikari, A.V.*
Photochemical and Photobiological Sciences, 2019, Vol.18, p2052

106. DEA dynamics of chlorine dioxide probed by velocity slice imaging
Gope, Krishnendu*; Mason, Nigel*; Krishnakumar, E.; et al.
Physical Chemistry Chemical Physics, 2019, Vol.21, p14023

107. Measuring spatially extended density profiles using atom-cavity collective strong coupling to higher-order modes
Niranjan, M.; Dutta, Sourav; Ray, Tridib; Rangwala, S.A.
Physical Review A, 2019, Vol.99, Article No:033617

108. Quantum properties of light propagating in a coherent-population-oscillation storage medium
Neveu, P.; Bretenaker, Fabien; Goldfarb, F.; Brion, E.
Physical Review A, 2019, Vol.100, Article No:013820

109. Near-100% two-photon-like coincidence-visibility dip with classical light and the role of complementarity
Sadana, Simanraj; Ghosh, Debadrita; Joarder, Kaushik; Lakshmi, A. Naga; Sanders, Barry C; Sinha, Urbasi
Physical Review A, 2019, Vol.100, Article No:013839

110. Broadcasting of quantum correlations in qubit-qudit systems
Rounak, Mundra*; Chatterjee, Sourav; Patel, Dhrumil* + 2 co-authors
Physical Review A, 2019, Vol.100, Article No:042319

111. Pearson correlation coefficient as a measure for certifying and quantifying high-dimensional entanglement
Jebarathinam, C.*; Home, Dipankar*; Sinha, Urbasi
Physical Review A, 2020, Vol.101, Article No:022112

112. Dynamics of hybrid junctions of Majorana wires
Bondyopadhaya, Nilanjan* and Dibyendu Roy
Physical Review B, 2019, Vol.99, Article No:214514

113. Ultrahigh energy cosmic rays and neutrinos from light nuclei composition
Das, Saikat; Gupta, Nayantara; Razzaque, Soebur*
Physical Review D, 2019, Vol.99, Article No:083015

114. Sorkin-Johnston vacuum for a massive scalar field in the 2D causal diamond
Mathur, Abhishek and Surya, Sumati
Physical Review D, 2019, Vol.100, Article No:045007

115. Quantum propagation in Smolin's weak coupling limit of 4D Euclidean gravity
Varadarajan, Madhavan
Physical Review D, 2019, Vol.100, Article No:066018

116. Run-and-tumble particle in one-dimensional confining potentials: Steady-state, relaxation, and first-passage properties
Dhar, Abhishek*; Kundu, Anupam*; Sabhapandit, Sanjib; Majumdar, Satya N*; Schehr, Grégory*
Physical Review E, 2019, Vol. 99, Article No:032132

117. Simple model for the stripe phase in compounds with bent-core molecules which exhibit a lower-temperature ferroelectric smectic-A phase
Madhusudana, N., V
Physical Review E, 2019, Vol.100, Article No:022706

118. Symmetric Exclusion Process under Stochastic Resetting
Urna Basu, Anupam Kundu*, Arnab Pal*
Physical Review E, 2019, Vol.100, Article No:032136

119. Long-time position distribution of an active Brownian particle in two dimensions
Basu, Urna; Majumdar, Satya N.*; Rosso, Alberto*; Schehr, Grégory*
Physical Review E, 2019, Vol.100, Article No:062116

120. Pseudopolar smectic-C phases of azo-substituted achiral bent-core hockey-stick-shaped molecules
Malkar, Deepshika; Monika, M.*; Prasad, Veena*; Roy, Arun
Physical Review E, 2020, Vol.101, Article No:012701

121. Saddle-splay-induced periodic edge undulations in smectic-A disks immersed in a nematic medium
Krishnamurthy, Kanakapura S*; Rao, Shankar D.S.*; Kanakala, Madhu B*; Yelamaggad, C.V.*; Madhusudana, N.V.
Physical Review E, 2020, Vol.101, Article No:032704

122. Mode Locking of the Hermite-Gaussian Modes of a Nanolaser
Sun, Yifan*; Combrie, Sylvain*; Bretenaker, Fabien; Rossi, Alfredo De*
Physical Review Letters, 2019, Vol.123, Article No:233901

123. A physical perspective on classical cloning
Reddy, Anirudh; Samuel, J; Sinha, Supurna
Physics letters A, 2019, Vol. 383, Article No:125846

124. Likelihood theory in a quantum world: Tests with quantum coins and computers
Maitra, Arpita*; Samuel, J.; Sinha, Supurna
Pramana, 2020, Vol.94 Article No:57

125. Broadcasting of entanglement via orthogonal and non-orthogonal state-dependent cloners
Shukla, Manish Kumar*; Chakrabarty, Indranil*; Chatterjee, Sourav
Quantum Information Processing, 2020, Vol.19, p18

126. Interaction of the mononucleotide UMP with a fluid phospholipid bilayer
Sasidharan, Sreeja; Pochinda, Simon*; Elgaard-Jorgensen, Paninnguaq Naja*; Rajamani , Sudha*; Khandelia Himanshu*; Raghunathan, V.A
Soft Matter, 2019, Vol.15, p8129

127. Strain softening and stiffening responses of spider silk fibers probed using a Micro-Extension Rheometer
Dubey, Sushil; Veer, Sukh; Majumdar, Sayantan; Pullarkat, Pramod A. + 4 co-authors
Soft Matter, 2020, Vol.16, p487

128. Self-assembled toron-like structures in inverse nematic gels
Topnani, Neha B; Posnjak, Gregor*; Prutha, N; Neogi, Arkalekha; Musevic, Igor*; Pratibha R
Soft Matter, 2020, Vol.16, p2875

129. Molecular structure, NLO properties and vibrational analysis of L-Histidine tetra fluro borate by experimental and computational spectroscopic techniques
John, Nimmy L ; Abraham, Sunila ; Sajan, D ; Philip, Reji ; Joy, Nithin and Chitra,R
Spectrochimica Acta Part A-Molecular and Biomolecular Spectroscopy, 2020, Vol.226, Article No:117615

Papers In Conference Proceedings

1. On Measuring the Deviation from the Superposition Principle in Interference Experiments
Rengaraj, G.; Prathwiraj, U.; Sinha, Urbasi
Conference: 6th IUPAP International Conference on Women in Physics (ICWIP) Location: Univ Birmingham, Birmingham, England, Jul 16-20, 2017
AIP Conference Proceedings, Women in Physics, 6th IUPAP International Conference on Women in Physics, 2019, p070001

2. Gender Status in the Indian Physics Profession and the Way Forward
Resmi, Lekshmi; Shastri, Prajval; Sinha, Urbasi; +7 Co-Authors
Conference: 6th IUPAP International Conference on Women in Physics (ICWIP) Location: Univ. Birmingham, Birmingham, England, JUL 16-20, 2017.
AIP Conference Proceedings, 2019, Vol. 2109, p050019

3. Design and Development of Digital Archives for Bio-bibliographic Representation
Hiremath, Vani and Meera, B M
Proceedings of International conference on digital Landscape: Digital Transformation for an agile Environment organized by TERI from 6-8 November, 2019, New Delhi. p256

4. Electric field tuning of ferroelectric liquid-crystal microlaser
Ryzhkova, A V; Pratibha, R; Nikkhou, Maryam and Muševič, I
Proceedings of the SPIE, Vol. 11303, p113030K-1, 2020, Emerging Liquid Crystal Technologies XV, Liang-Chy Chien, Dirk J. Broer

Popular Articles

1. New insights into the biomechanics of axonal atrophy can aid in finding a cure to neurodegenerative conditions
Pullarkat, Pramod A
Research Matters, December 4, 2019 (https://researchmatters.in/news/new-insights-biomechanics-axonal-atrophy-can-aid-finding-cure-neurodegenerative-conditions)

2. 'Desh' literary magazine(Bengali) , 2 August 2019- on forensic science
Nath, Biman B

3. The Tripl Slit Experiment
Sinha, Urbasi
Scientific American (Invited), January 2020 issue

Book Chapters

1. Stabilization of Discotic Liquid Crystals
Yuvaraj, A R & Kumar, Sandeep
Polymer-modified Liquid Crystals, Edited by Ingo Dierking, RSC Publishing (Book Chapter-15), 2019, p 332

2. Measurements of Temporal Fluctuations of Magnetization in Alkali Vapor and Applications
Swar, Maheswar; Roy, Dibyendu; Dhanalakshmi, D; Chaudhuri, Saptarishi; Roy, Sanjukta; Ramachandran, Hema
Emerging Trends in Advanced Spectroscopy, Edited by Weiman, Yang; Jibin, K p et. al, River Publishers Series in Optics and Photonics, (Book Chapter – 11), 2019, p113

3. Liquid crystalline polymers derived from disc-shaped Molecules
Setia, Shilpa; Kumar, Sandeep and Pal, Santanu Kumar
Polymers and Polymeric Composites: A Reference Series, Palsule S. (eds) Springer, Berlin, Heidelberg, 1-35, 2019

Miscellaneous

1. Mathematical models for the spread of Covid-19
Samuel, Joseph and Sinha, Supurna
Social media, April 16, 2020

Papers in Press – In Journals

1. Theranostic lyotropic liquid crystalline nanostructures for selective breast cancer imaging and therapy
Urandur, Sandeep; Banala, Venkatesh Teja; Pratibha, R + 7 Co-authors
Acta Biomaterialia, 2020

2. Gamma-Ray Flares in the Long-term Light Curve of 3C 454.3
Das, Avik Kumar; Prince, Raj and Gupta, Nayantara
Astrophysical Journal Supplement Series, 2020, Vol.248, Article No.8

3. Influence of particle size on the thermoresponsive and rheological properties of aqueous poly (N-isopropylacrylamide) colloidal suspensions
Chandeshwar Misra, Sanjay Kumar Behera and Ranjini Bandyopadhyay
Bulletin of Materials Science, 2020

4. Symmetry-breaking and zero-one laws
Dowker, Fay and Sorkin, Rafael D
Classical and Quantum Gravity, 2020, Vol. 37, Article No.155007

5. The axonal actin-spectrinlattice acts as shock absorbers to protect neurons from stretch-induced damage
Sushil Dubey; Nishita Bhembre*; Aurnab Ghose*; Andrew Callan-Jones*; Pramod A Pullarkat
eLife, 2020, Vol. 9, p e51772

6. SARAS CD/EoR Radiometer: Design and performance of the digital correlation spectrometer
Girish, B S; Srivani, K S; Subrahmanyan, Ravi; Udaya Shankar, N; Singh, Saurabh; Nambissan, Jishnu T; Rao, Mayuri Sathyanarayana; Somashekar R and Raghunathan A
Journal of Astronomical Instrumentation, 2020, Vol.9, Article No. 2050006

7. Orientational probability distribution of an active Brownian particle: an analytical study
Sinha, Supurna
Journal of Statistical Mechanics: Theory and Experiment, 2020, Article No: 013204

8. Carbon dot-dispersed hexabutyloxytriphenylene discotic mesogens: structural, morphological and charge transport behavior†
Pruthvi Mahesh; Asmita Shah*; K. Swamynathan, Pratap Singh, Dharmendra*; Doualib, Redouane* and Kumar, Sandeep
Journal of Materials Chemistry C, 2020, Vol.9, p9252

9. Effect of manganese doping on the structural, morphological, optical, electrical, and magnetic properties of BaSnO3
John, Jibi*; Dhananjaya*, Philip, Reji and 5 Co-authors
Journal of Materials Science: Materials in Electronics (2020) 31:11159–11176

10. Synthesis and third order optical nonlinearity studies of toluidine tartrate single crystal supported by photophysical characterization and vibrational spectral analysis
George, Merin*; Balaji,J*; Sajan,D*; Dominic,P; Philip,Reji and Vinitha, G*
Journal of Photochemistry and Photobiology A: Chemistry, 2020, Vol.393, p112413

11. Effect of adsorbed polyelectrolytes on the interactions and elasticity of charged surfactant bilayers.
Gupta, Santosh Prasad*; Thomas, Meera; Chowdhury, Anindya and Raghunathan, V A
Journal of Physics: Condensed Matter, 2020, Vol. 32, Article No.194004

12. Tuneable ferroelectric liquid crystal microlaser
Ryzhkova, A V; Pratibha, R. and Muševič, I
Liquid Crystals, 2020, Vol.47, p994

13. Predictions for measuring the 21-cm multi-frequency angular power spectrum using SKA-Low
Mondal, Rajesh*; Shaw, Abinash Kumar*; Sarkar, Anjan Kumar +5 Co-Authors
Monthly Notices of the Royal Astronomical Society, 2020, Vol.494, p4043

14. Mean field dynamo action in shear flows. I: fixed kinetic helicity
Jingade, Naveen and Singh, Nishant K
Monthly Notices of the Royal Astronomical Society, 2020, Vol.495, p4557

15. Passive spirals and shock influenced star formation in the merging cluster A3376
Kelkar, Kshitija; Dwarakanath, K S; Poggianti, Bianca M*
Monthly Notices of the Royal Astronomical Society, 2020, Vol.496, p442

16. Amplification and cross-Kerr nonlinearity in waveguide quantum electrodynamics
Vinu, Athul and Roy, Dibyendu
Physical Review A, 2020, Vol.101, Article No.053812

17. Stability of topological wall defects in spheres with n-atic order
Saichand C; Alageshan, Jaya Kumar; Roy, Arun; Hatwalne, Yashodhan
Physical Review Research, 2020, Vol.2, Article No. 023215

18. Solvothermal synthesis of nanoscale disc like gadolinium doped magnesium zirconate for highly efficient photocatalytic degradation of rhodamine B in water
S. Akshatha, S S. Sreenivasa,S S; Kumar, Sandeep + 5 Co-authors
SN Applied Sciences, 2020, Vol.2, p876

Conferences Attended & Institutions Visited

Appendix - II

Name	Conferences attended / Institutions visited	Title of paper/talk
Alakananda Patra	26th National Conference on Liquid Crystals Chitkara University, Punjab 21 – 23 October 2019 International Winter School Jawaharlal Nehru Centre for Advanced Scientific Research, Bengaluru 2 – 6 December 2019	Phenazine-fused triphenylene discotic liquid crystals Phenazine-fused triphenylene discotic liquid crystals
Andal Narayanan	International Conference on Quantum Frontiers and Fundamentals Raman Research Institute, Bengaluru 13 – 18 January 2020	
Anjan Kumar Sarkar	Vigyan Samagam - Pushing the Frontiers of Science Visvesvaraya Industrial & Technological Museum, Bengaluru 10 – 14 September 2019	
Arasi Sathyamurthy	2nd Annual Meeting of Modern Engineering Trends in Astronomy 2019 Indian Institute of Astrophysics, Bengaluru 15 – 17 September 2019	Modern engineering trends in astronomy
Avinash Deshpande	Bishop Heber College, Tiruchirapalli 1 August 2019 Inter-University Centre for Astronomy and Astrophysics, Pune 20 – 24 August 2019 Workshop on Application of Engineering to Astronomy Viswakarma Institute of Technology, Pune 22 August 2019 Arecibo Observatory, USA 21 September – 6 October 2019	Radio astronomy *(2 lectures)* On attempts to detect EoR global signal, and SWAN Radio astronomy basics 1.Fascinating life-stories of cosmic light-houses 2.Radio frequency interference: To avoid or attack? 3.Sky watch array network: A strategic initiative

Name	Conferences attended / Institutions visited	Title of paper/talk
	Australia-India Research & Development in Radio Astronomy Meeting National Centre for Radio Astronomy, Pune 13 - 15 November 2019	Indian SWAN *(Invited)*
	National Institute of Technology, Surathkal 25 – 27 December 2019	Fascinating life-stories of cosmic light-houses
Biman Nath	Saha Equation Centenary Conference Calcutta University, Kolkata 23 September 2019	
	Conference on Supermassive Black Holes International Center for Theoretical Sciences Bengaluru 19 December 2019	
Chandeshwar Misra	Complex Fluids Meeting 2019 Indian Institute of Science Education & Research, Bhopal 5 – 7 December 2019	
Dibyendu Roy	University of Ljubljana, Slovenia 28 April – 25 May 2019	An open-quantum system description of Josephson effect in topological superconductors
	Conference on Thermalization, Many body Localization and Hydrodynamics International Centre for Theoretical Sciences India 11 – 29 November 2019	Pancharatnam-Zak phase
Dwarakanath KS	National Radio Astronomy Observatory Mexico 9 – 13 September 2019	Diffuse radio emission in galaxy clusters
	Case Western Reserve University, Ohio 16 – 20 September 2019	Diffuse radio emission in galaxy clusters
Girish BS	Vigyan Samagam - Pushing the Frontiers of Science Visvesvaraya Industrial & Technological Museum, Bengaluru 10 – 14 September 2019	Architectures for digital signal processing in radio astronomy *(Invited)*
	2nd Annual Meeting of Modern Engineering Trends in Astronomy 2019 Indian Institute of Astrophysics, Bengaluru 15 – 17 September 2019	Challenges in designing receiver for detection of signals from the Epoch of Reionisation

Name	Conferences attended / Institutions visited	Title of paper/talk
	Conference on IESA Spacetronics & Deftronics 2019 Taj Yeshwantpur, Bengaluru 19 – 20 September 2019 Australia-India Research & Development in Radio Astronomy Meeting National Centre for Radio Astronomy, Pune 13 - 15 November 2019	 Ongoing developments and plans for low-frequency digital receiver platforms
Jishnu Nambissan	Conference on The First Billion Year of the Universe Indian Institute of Technology, Indore 20 – 24 January 2020 Netherlands Institute for Radio Astronomy The Netherlands 4 June – 28 August 2019	Updates from SARAS *(Invited)*
Joseph Samuel	Chennai Mathematical Institute, Chennai 21 – 22 May 2019 Institute of Mathematical Sciences, Chennai 23 – 24 May 2019 Conference on Quantum Frontiers & Fundamentals Raman Research Institute, Bengaluru 13 – 18 January 2020 Conference on Geometric Phases in Optics and Topological Matter International Centre for Theoretical Sciences Bengaluru 21 – 24 January 2020	Lorentzian geometry of qubit entanglement Lorentzian geometry of qubit entanglement 1.Geometric phase and DNA elasticity 2.Controlling entanglement with the geometric phase
Kasturi S	2nd Annual Meeting of Modern Engineering Trends in Astronomy 2019 Indian Institute of Astrophysics, Bengaluru 15 – 17 September 2019	
Krishnakumar E	Tata Institute of Fundamental Research Hyderabad 13 May 2019 XX International Workshop on Low-Energy Positron and Positronium Physics XXI International Symposium on Electron-Molecule Collisions and Swarms	Negative ion states of molecular hydrogen: Quantum dynamics of five particle system Functional group dependence and site selectivity in dissociative attachment *(Invited)*

Name	Conferences attended / Institutions visited	Title of paper/talk
	Serbian Academy of Sciences and Arts Serbia 18 – 20 July 2019	
	XXXI International Conference on Photonic, Electronic and Atomic Collisions Deauville International Center, France 24 – 30 July 2019	Probing functional group dependence in dissociative electron attachment using negative ion momentum imaging
Kshitija Kelkar	Conference on Pressing for Progress 2019 University of Hyderabad, Telangana 19 – 21 September 2019	
	XXXVIII Astronomical Society of India Conference Indian Institute of Science Education and Research, Tirupati 13 – 17 February 2020	Passing spirals and shock-induced star formation in merging cluster Abell 3376
Madhavan Varadarajan	Delhi University, New Delhi 30 April 2019	Loop quantum gravity: An overview
	Complutense University, Spain 26 June 2019	Loop quantum gravity: A structural overview
	Consejo Superior de Investigaciones Cientificas, Spain 22 June – 1 July and 6 – 7 July 2019	Propagation in canonical LQG
	Centre de physique théorique, France 2 – 5 July 2019	1.Loop quantum gravity: A structural overview 2.Spacetime covariance and propagation in canonical LQG
	Friedrich–Alexander University Erlangen–Nürnberg, Germany 14 – 25 July 2019	1.Loop quantum gravity: A structural review 2.Propagation in canonical loop quantum gravity
	Inter University Centre for Astronomy & Astrophysics, Pune 17 – 19 October 2019	Loop quantum gravity
	Indian Institute of Science Education and Research, Pune 9 – 10 November 2019	
	Seminar on International Loop Quantum Gravity 31 March 2020	Spacetime covariance and propagation in canonical loop quantum gravity *(Online)*

Name	Conferences attended / Institutions visited	Title of paper/talk
Manjunath M	Vigyan Samagam: Pushing the Frontiers of Science Visvesvaraya Industrial & Technological Museum, Bengaluru 10 – 14 September 2019	
Mayuri S	18th International Workshop on Low Temperature Detectors, Italy 22 – 26 July 2019 CMR Institute of Technology, Bengaluru 8 August 2019 Second Global 21-cm Workshop McGill University, Canada 7 – 9 October 2019	 BE ECE to cosmology *(remote talk)*
Mugundhan V	Vigyan Samagam- Pushing the Frontiers of Science Visvesvaraya Industrial & Technological Museum, Bengaluru 10 – 14 September 2019	How to see with many eyes
Nagaraj MN	Meeting on Libraries and Librarians - New Education Policy 2019 Raman Research Institute, Bengaluru 20 July 2019	
Nayantara Gupta	First CTA Symposium Teatro Duse, Italy 6 – 9 May 2019 Laboratoire d'Annecy-le-Vieux de Physique Théorique, France 10 – 17 May 2019 Nicolaus Copernicus Astronomical Center Poland 18 – 24 May 2019 National Conference on Transient Astronomy UR Rao Satellite Centre, Bengaluru 11 – 12 November 2019	Constraining the halo size from possible density profiles of milky way galaxy Multi-messenger astronomy IceCube neutrino events and blazar flares
Palak	Complex Fluids Meeting 2019 Indian Institute of Science Education & Research, Bhopal 5 – 7 December 2019	Study of instabilities at the interface of Newtonian and non-Newtonian fluid in a quasi-two dimensional geometries

Name	Conferences attended / Institutions visited	Title of paper/talk
Prabu T	2nd Annual Meeting of Modern Engineering Trends in Astronomy 2019 Indian Institute of Astrophysics, Bengaluru 15 – 17 September 2019	1.Accelerated tile processor 2.21 cm horn receiver
	Global Workshop on NAND FLASH Jain University, Bengaluru 23 September 2019	How storage contributes to research today in radio astronomy *(Invited)*
	Australia-India Research & Development in Radio Astronomy Meeting National Centre for Radio Astronomy Pune 13 - 15 November 2019	Digital signal processing and possible collaboration areas
	2019 SKA Shanghai Meeting Wanda Reign, China 25 – 28 November 2019	Experiences for commissioning MWA digital receivers
	Conference - URSI RCRS Indian Institute of Technology, Varanasi 12 – 14 February 2020	The SKA low frequency aperture array – An engineering overview *(Invited)*
	Science Week Global Academy of Technology, Bengaluru 9 – 13 March 2020	An overview of developments and advancements in scientific arena *(Invited)*
Pramod Pullarkat	Institute Curie, France 11 September 2019	Mechanical and shape responses of axons
	University of Strasbourg, France 18 September 2019	Mechanical and shape responses of axons
	University of Geneva, Switzerland 24 September 2019	Mechanical and shape responses of axons
	Indian Institute of Science, Bengaluru 3 October 2019	Mechanical responses of cells
	Molecular Motors, Transport and Trafficking Meeting National Brain Research Center, Gurugram 18 – 20 October 2019	Mechanical and shape responses of axons
	Indian Institute of Technology, Madras Chennai 30 October 2019	Mechanical responses of cells
	Complex Fluids Meeting 2019 Indian Institute of Science Education &	

Name	Conferences attended / Institutions visited	Title of paper/talk
	Research, Bhopal 5 – 7 December 2019	
	Ramaiah Institute of Technology Bengaluru 17 January 2020	Mechanical and shape responses of axons
	International Symposium on Cell Surface Macromolecules Indian Institute of Science Education and Research, Pune 2 – 6 February 2020	Actin dynamics in axonal membrane nano-tubes
	Fluctuations in Nonequilibrium Systems: Theory and Applications 2020 School International Center for Theoretical Sciences Bengaluru 9 - 10 March 2020	1. Lipid membranes and fluctuations 2. Axon mechanics
Pratibha R	British Liquid Crystal Society Annual Conference University of Leeds, UK 15 – 17 April 2019	Unusual forms of liquid crystal-fibre self-assembly *(Sturgeon Lecture – Invited, Plenary)*
	Complex Fluids Meeting 2019 Indian Institute of Science Education and Research, Bhopal 5 – 7 December 2019	Blue phase stabilization in a binary mixture of chiral and achiral molecules *(Invited)*
Raghavendra Rao KB	2nd Annual Meeting of Modern Engineering Trends in Astronomy 2019 Indian Institute of Astrophysics, Bengaluru 15 – 17 September 2019	Sky Watch Array Network (SWAN): Wide-band receiver instrumentation development and current status
Raghunathan A	2nd Annual Meeting of Modern Engineering Trends in Astronomy 2019 Indian Institute of Astrophysics, Bengaluru 15 – 17 September 2019	
Raghunathan VA	Complex Fluids Meeting 2019 Indian Institute of Science Education & Research, Bhopal 5 – 7 December 2019	Effect of adsorbed polyelectrolytes on the interactions and elasticity of charged surfactant bilayers *(Invited)*
	International Symposium on Cell Surface Macromolecules Indian Institute of Science Education and Research, Pune 17 – 21 February 2020	Fluid-fluid coexistence in lipid-sterol membranes *(Invited)*

Name	Conferences attended / Institutions visited	Title of paper/talk
Rajkumar Biswas	Complex Fluids Meeting 2019 Indian Institute of Science Education & Research, Bhopal 5 – 7 December 2019	
Ramesh Balasubramanyam	Indian Astronomical Observatory Hanle 12 – 18 January 2020	
	Indian Conference on Antenna & Propagation 2019 Hotel Narayani Heights, Ahmedabad 19 – 22 December 2019	On road to terahertz astronomy from India *(Invited)*
	XXXVIII Astronomical Society of India Conference Indian Institute of Science Education and Research, Tirupati 13 – 17 February 2020	Building RRI efficient linear-array imager
Ranita Jana	XXXVIII Astronomical Society of India Conference Indian Institute of Science Education and Research, Tirupati 13 – 17 February 2020	Role of cosmic rays in the early stages of galactic outflows
Ranjini Bandyopadhyay	3rd Departmental Symposium on Advances in Physics Indian Institute of Technology, Delhi 6 – 7 April 2019	Electric field induced gelation in soft colloidal clay suspensions *(Invited)*
	College Summer Course Jawaharlal Nehru Planetarium, Bengaluru 30 May 2019	Electric field induced gelation in aqueous colloidal clay suspensions *(Invited)*
	Conference on Pressing for Progress University of Hyderabad, Telangana 19 – 21 September 2019	Our experiments with colloidal clays *(Invited)*
	Conference on Physics at Surfaces and Interfaces of Soft Materials Jadavpur University, Kolkata 26 – 27 September 2019	The effect of activity on the colloidal glass transition *(Invited)*
	Conference on Statphys Kolkata – X Presidency University 26 – 29 November 2019	A study of the instability at the interface between a Newtonian and a non-Newtonian *(Invited)*

Name	Conferences attended / Institutions visited	Title of paper/talk
	7th Indian Statistical Physics Community Meeting International Centre for Theoretical Sciences Bengaluru 19 – 21 February 2020	Measuring the correlated dynamics in dense suspensions of highly polydisperse poly (N-isopropylacrilamide) microparticles
	Conference on Fluctuations in Non-equilibrium Systems: Theory and Applications International Centre for Theoretical Sciences Bengaluru 9 – 19 March 2020	Experiments with active particles in a dense environment of passive particles *(Invited)*
Reji Philip	International Conference on Advanced Materials Nirmalagiri College, Kerala 12 – 14 June 2019	Optical power limiting: Materials and methods *(Invited)*
	Summer School on Optics and Applied Photonics Indian Institute of Science, Bengaluru 17 – 21 June 2019	Light-matter interactions in the intense field regime *(Invited)*
	Kerala University, Trivandrum 24 June 2019	Optical power limiting: Materials and methods *(Invited)*
	MVJ College of Engineering, Bengaluru 5 October 2019	Fundamentals of lasers *(Invited)*
	Govt. Victoria College, Palakkad 16 October 2019	Linear and nonlinear optical characterization techniques
	Indian Institute of Technology, Guwahati 1 November 2019	Ultrafast laser produced plasmas: generation, characterization and applications
	National Conference on Advanced Materials St. Joseph's College, Tiruchirapalli 13 December 2019	Nonlinear optics in the nano domain: Materials and methods *(Invited)*
	International Conference on Frontiers of Material Science St. Joseph's College, Calicut 16 – 18 December 2019	Nonlinear optics in the nano domain: Materials and methods *(Invited)*
	National Conference on Recent Trends in Materials Science and Technology Indian Institute of Space Science and Technology, Trivandrum 18 – 20 December 2019	Nonlinear optics in the nano domain: Materials and methods *(Invited)*

Name	Conferences attended / Institutions visited	Title of paper/talk
	107th Indian Science Congress Gandhi Krishi Vigyana Kendra, Bengaluru 3 – 7 January 2020	Optical limiters: Materials for protecting human eyes and optical sensors from hazardous laser radiation *(Invited)*
	International Conference on the Science and Technology of Advanced Materials MA College, Kothamangalam 14 – 16 January 2020	Nonlinear optics in the nano domain: Materials and methods *(Invited)*
	Karnataka Science and Technology Academy Gandhi Krishi Vigyana Kendra Campus Bengaluru 23 January 2020	Nonlinear optics in the nano domain: Materials and methods
	National Workshop on Emerging Trends in Physics and Their Applications Gitam University, Bengaluru 28 February 2020	Nonlinear optics: Theory and applications *(Invited)*
	29th Swadeshi Science Congress, National Conference on Science and Technology for Sustainable Development ICAR-Central Plantation Crops Research Institute, Kasaragod 29 February 2020	The Raman effect *(Invited)*
	8th Topical Conference of the Indian Society for Atomic and Molecular Physics Indian Institute of Technology, Roorkee 3 – 5 March 2020	Multidiagnostic characterization of ultrashort and short pulse laser produced plasmas *(Invited)*
Rishin PV	XXXVIII Astronomical Society of India Conference Indian Institute of Science Education and Research, Tirupati 13 – 17 February 2020	Current status of POLIX, an X-ray Polarimeter on-board XPoSat *(Invited)*
Sadiq Rangwala	XXXI International Conference on Photonic, Electronic and Atomic Collisions Deauville International Center, France 23 – 30 July 2019	Collisional cooling of trapped ions with atoms: Results and insights
	IISc-CERN Symposium on New Frontiers in Physics Indian Institute of Science, Bengaluru 4 September 2019	Combined atom-ion-molecule-light traps and what they are good for
	University of Basel, Switzerland 16 October 2019	Combined atom-ion-molecule-light traps and what they are good for

Name	Conferences attended / Institutions visited	Title of paper/talk
	IPA PK Iyengar Award Tata Institute of Fundamental Research Mumbai 4 November 2019	Interactions in trapped cold gases
Sanjib Sabhapandit	7th Indian Statistical Physics Community Meeting International Centre for Theoretical Sciences Bengaluru 19 – 21 February 2020	Kramers barrier crossing problem and the first-passage time distribution
Saptarishi Chaudhuri	International Conference of Physics and Allied Sciences, Bidar 11 – 13 March 2020	Quantum technology with ultra-cold atoms *(Invited)*
Sayantan Majumdar	Summer Program on From the Web of Universe to Life Jawaharlal Nehru Planetarium, Bengaluru 29 May 2019	Shear jamming in dense particulate suspensions *(Invited)*
	International Soft Matter Conference 2019 University of Edinburgh, UK 3 – 7 June 2019	Shear induced jamming and yielding in dense particulate suspensions
	International Conference on Polymer Processing and Characterization Mahatma Gandhi University, Kerala 11 – 13 October 2019	Signature of jamming under steady shear in dense particulate suspensions *(Invited)*
	Complex Fluids Meeting 2019 Indian Institute of Science Education & Research, Bhopal 5 – 7 December 2019	Signature of jamming under steady shear in dense particulate suspensions *(Invited)*
	Fluids Day International Centre for Theoretical Sciences Bengaluru 20 January 2020	Jamming under steady shear in dense particulate suspensions
	7th Indian Statistical Physics Community Meeting International Centre for Theoretical Sciences Bengaluru 19 – 21 February 2020	Signature of jamming under steady shear in dense particulate suspensions
Sebanti Chattopadhyay	Complex Fluids Meeting 2019 Indian Institute of Science Education & Research, Bhopal 5 – 7 December 2019	Yielding in dense suspensions of cohesive amorphous particles

Name	Conferences attended / Institutions visited	Title of paper/talk
Somashekar R	Vigyan Samagam - Pushing the Frontiers of Science Visvesvaraya Industrial & Technological Museum, Bengaluru 10 – 14 September 2019	RF electronics for radio astronomy
	2nd Annual Meeting of Modern Engineering Trends in Astronomy 2019 Indian Institute of Astrophysics, Bengaluru 15 – 17 September 2019	An overview of analog receiver system for detection of global EoR signal
	Conference on IESA Spacetronics & Deftronics 2019 Taj Yeshwantpur, Bengaluru 19 – 20 September 2019	
	Australia-India Research & Development in Radio Astronomy Meeting National Centre for Radio Astronomy, Pune 15 November 2019	Precision analog receiver system for EoR
	Space Application Centre, Ahmedabad 3 – 4 March 2020	Analog receiver system of SARAS 3 – ground based system
Sridhar S	Inter-University Centre for Astronomy and Astrophysics, Pune 25 – 27 September 2019	Theory of spiral structure in disc galaxies
	CAMS@20 American University of Beirut, USA 28 – 30 November 2019	Galaxy dynamics and kinetics *(Plenary, Invited)*
	American University of Beirut, USA 25 November – 6 December 2019	Dynamics of stellar systems
	Indian Institute of Technology Madras Chennai 26 – 27 February 2020	Structure and dynamics of galaxies
Srinivasa HT	International Conference on Liquid Crystals, Liquid Crystalline Polymers and Nanosystems 2019 Mahatma Gandhi University, Kerala 13 -15 December 2019	Nemtic and switchable intercalated phases in polymerizable bent-core monomers with naphthalene moiety in the side arms of the aromatic core *(Invited)*
Srivani KS	Vigyan Samagam - Pushing the Frontiers of Science Visvesvaraya Industrial & Technological Museum, Bengaluru 10 – 14 September 2019	State-of-the-art technology transforming the radio astronomy signal processing

Name	Conferences attended / Institutions visited	Title of paper/talk
	Conference on IESA Spacetronics & Deftronics 2019 Taj Yeshwantpur, Bengaluru 19 – 20 September 2019	
	Australia-India Research & Development in Radio Astronomy Meeting National Centre for Radio Astronomy, Pune 13 - 15 November 2019	Wide band digital tile processing system for low frequency array
	UR Rao Satellite Centre, Bengaluru 11 January 2020	PRATUSH
	Indian Space Research Organisation Bengaluru 23 January 2020	PRATUSH-C3
	UR Rao Satellite Centre, Bengaluru 25 February 2020	PRATUSH-C3
	Space Applications Centre, Ahmedabad 2 – 3 March 2020	
Sumati Surya	Azim Premji University, Bengaluru 12 September 2019	Light, gravity, action!
	Conference on Quantum Gravity in Paris Institut Henri Poincare, Paris 15 – 19 April 2019	Causal set theory: Recent developments and challenges *(Plenary)*
	Imperial College, UK 21 – 26 April 2019	
	22nd edition of the International Conference on General Relativity and Gravitation Valencia, Spain 7 – 12 July 2019	A status report on causal set theory *(Invited)*
	The Time Machine Factory Conference 2019 Universit degli Studi di Torino, Italy 22 – 26 September 2019	a.The role of causality in quantum gravity *(Plenary)* b.The genius syndrome: Gender in the practice of Theoretical Physics *(Invited)*
	Perimeter Institute, Canada 13 – 18 October 2019 10 – 24 November 2019	
	Conference on Everpresent Lambda Perimeter Institute, Canada 11 – 15 November 2019	An introduction to causal sets *(Invited)*

Name	Conferences attended / Institutions visited	Title of paper/talk
Sumanth Kumar	64th Annual Meeting of the Biophysical Society San Diego, USA 15 – 19 February 2020	Detection of nucleosome-RCC1 complexes using nanopares
Supurna Sinha	Chennai Mathematical Institute, Chennai 21 – 22 May 2019 Institute of Mathematical Sciences, Chennai 23 – 24 May 2019 International Conference on Quantum Frontiers and Fundamentals 13 – 18 January 2020 Conference on Geometric Phases in Optics and Topological Matter International Centre for Theoretical Sciences Bengaluru 21 – 24 January 2020	A quantum diffusion law A quantum diffusion law 1.Geometric phase and DNA elasticity 2.Controlling entanglement with the geometric phase
Tanuman Ghosh	Young Astronomers' Meet Indian Institute of Astrophysics, Kodaikanal 23 – 27 September 2019 National Conference on Transient Astronomy UR Rao Satellite Centre, Bengaluru 11 – 12 November 2019	Ultra-luminous X-ray sources – black holes or neutron stars? M33 X-8: A case study Enigmatic nature of ultraluminous X-ray sources *(Invited)*
Urbasi Sinha	C-DAC Technology Conclave C-DAC Innovation Park, Pune 4 – 5 April 2019 University of Science and Technology, China 4 June 2019 ITU Workshop on Quantum Information Technology for Networks, China 5 – 7 June 2019 Summer School on Quantum Information and Quantum Technology Indian Institute of Science Education and Research, Kolkata 3 July 2019 University College London, UK 11 July 2019	Quantum computing and quantum communication *(Invited, Expert)* Hong-Ou-Mandel effect: New surprises and revelations *(Invited)* Spatial bin qudits: A potential candidate for higher dimensional quantum computing *(Invited, Expert)* 1.Single photon sources 2.Quantum communications On superposition, interference and Feynman paths

Name	Conferences attended / Institutions visited	Title of paper/talk
	OPTO 2019 Nicolaus Copernicus University, Poland 23 – 27 July 2019	Hong-Ou-Mandel effect: New surprises and revelations *(Invited, Expert)*
	University of Innsbruck, Austria 29 July 2019	Hong-Ou-Mandel effect: New surprises and revelations *(Invited)*
	Colloquium on Manipulating Light Quanta University of Trento, Italy 25 September 2019	
	TESSARACT 2019 Pandit Deendayal Petroleum University Gandhinagar 9 – 10 November 2019	Fascinating world of photons *(Invited)*
	Quantum Computing Workshop International Institute of Information Technology, Hyderabad 16 November 2019	Experimental quantum computing and quantum cryptography by manipulating light quanta *(Invited, Expert)*
	Indo-German Symposium on Quantum Science and Technologies Indian Institute of Technology, Madras Chennai 9 – 10 February 2020	Quantum communication at RRI Bangalore *(Invited)*
	National Science Day Indian Institute of Science Education and Research, Kolkata 28 February 2020	Quantum experiments using satellite technology *(Plenary)*
Urna Basu	University of Paris-Sud, France 2 September – 1 October 2019	
	Institute for Theoretical Physics Belgium 2 – 5 October 2019	
	International School for Advanced Studies Italy 5 – 9 October 2019	
	Statphys-Kolkata X Presidency College, Kolkata 26 – 29 November 2019	Active Brownian motion in two dimensions *(Invited)*
	Indian Statistical Physics Community Meeting International Centre for Theoretical Sciences Bengaluru 19 – 21 February 2020	Symmetric exclusion process under stochastic resetting

Name	Conferences attended / Institutions visited	Title of paper/talk
Vani Hiremath	EBSCO IEEE Knowledge Feast EBSCO Information Services India Bengaluru 8 August 2019	
Vanishree Bhat S	26th National Conference on Liquid Crystals Chitkara University, Punjab 21 – 23 October 2019	Synthesis and characterization of some liquid crystalline steroidal esters
Vikram Rana	National Conference on Transient Astronomy UR Rao Satellite Centre, Bengaluru 11 – 12 November 2019 Hard X-ray Optics Meeting Physical Research Laboratory, Ahmedabad 4 – 5 December 2019 DAKSHA Meeting Indian Institute of Technology, Bombay Mumbai 6 -7 March 2020	
Vinutha C	2nd Annual Meeting of Modern Engineering Trends in Astronomy 2019 Indian Institute of Astrophysics, Bengaluru 15 – 17 September 2019	
Vivek M Vyas	Conference on Geometric Phases in Optics and Topological Matter International Centre for Theoretical Sciences Bengaluru 21 – 24 January 2020	Pancharatnam-Zak phase *(Invited)*

Colloquia and Seminars

Appendix - III

Name	Title	Date
LS Shashidhara Indian Institute of Science Education and Research, Pune	Evolution of human cognition	04 April 2019
Apurva Oza University of Bern, Switzerland	Illuminating the magnetospheres of close-in gas giant exoplanets: Metallic signatures of volcanic Exomoons	08 April 2019
Frederick J Raab LIGO Laboratory, Washington	The bright future of gravitational-wave astronomy	15 April 2019
Torsten Langer PicoQuant GmbH, Germany	Single photon counting in optical quantum technologies	23 April 2019
Deepak Nair Indian Institute of Science, Bengaluru	Real-time nanoscale determinants involved in the localization and regulation of amyloidogenic processing of APP	10 May 2019
Roger Bilham University of Colorado, USA	Does earth's variable rotation influence global seismicity at decadal periods?	30 May 2019
Chris Stewart University of Sydney, Australia	A random walk: Finding an alternative career in physics	07 June 2019
Vivek Venkatraman Krishnan Max Planck Institute for Radio Astronomy Germany	Gravitational dynamics of relativistic binary pulsar systems	12 June 2019
Atanu Bhattacharya Indian Institute of Science, Bengaluru	Attosecond (10^{-18} second) charge migration	17 June 2019
Tanumoy Pramanik - Webinar Korea Institute of Science and Technology Korea	Theoretical and experimental studies of different quantum correlations and their applications	19 June 2019
Amitabh Virmani Chennai Mathematical Institute, Chennai	Aretakis instability	20 June 2019
Sayantan Choudhury Max Planck Institute for Gravitational Physics Germany	Open quantum field theory of many body entanglement in De Sitter Space	20 June 2019
Claude Fabre Laboratoire Kastler Brossel Université Pierre et Marie Curie, Paris	Generation of gaussian and non-gaussian multimode entangled states of light for applications to quantum information processing	21 June 2019
Kshitij Aggarwal West Virginia University, USA	Detection, localization and automated classification of fast radio bursts	24 June 2019

Name	Title	Date
Tom Lubensky University of Pennsylvania, USA	Monolayer membranes and confinement effects in chromonic liquid crystals	04 July 2019
Arijit Sharma Indian Institute of Technology, Tirupati	Progress towards parity violation measurements in dysprosium	05 July 2019
Nirmal Kumar Iyer KTH Royal Institute of Technology, Sweden	Instrumentation for hard X-ray polarimetry	12 July 2019
Sonali Sachdeva Kavli Institute for Astronomy & Astrophysics Beijing	Formation of disc galaxies around redshift2	16 July 2019
Apurva Oza University of Bern, Switzerland	Lecture series on 'Introduction to planetary astrophysics'	10, 12 & 16 July 2019
Sachin Barthwal Chinese Academy of Sciences, China	Tapered amplifier characterization technique for atom interferometry and other precision measurements	18 July 2019
Debasish Chaudhuri Institute of Physics, Bhubaneswar	Entropic organization of bacterial chromosome set by the cellular confinement and cytosolic crowding	19 July 2019
Krishnapriya SR Okinawa Institute of Science and Technology Japan	Formation of Rydberg atoms near an optical nanofibre	22 July 2019
Abhishodh Prakash International Centre for Theoretical Sciences Bengaluru	Invertible gapped phases of matter, their boundary anomalies and emergent symmetries	23 July 2019
AV Radhakrishnan Université de Bordeaux, France	Surpassing Abbe limit, going beyond Cramer-Rao Lower Bound and seeing the eLyrae7: An expedition with DNA-PAINT, Origamis and Cells	26 July 2019
Philip Diamond Square Kilometre Array, UK	SKA: exploring the origins of the universe and of life	30 July 2019
Shauri Chakraborty SN Bose National Centre for Basic Sciences Kolkata	Dynamics of propagating modes and characterisation of ordering in coupled non-equilibrium systems	19 August 2019
CS Unnikrishnan Tata Institute of Fundamental Research Mumbai	The theories of relativity, time, and simultaneity during and after Einstein's 1922 visit to Paris	22 August 2019
CS Unnikrishnan Tata Institute of Fundamental Research Mumbai	Quantum mechanics without foundational problems from modified Hamiltonian mechanics	23 August 2019

Name	Title	Date
Raghavendra Gadagkar Indian Institute of Science, Bengaluru	Can we understand an insect society, and why should we care?	29 August 2019
GC Anupama Indian Institute of Astrophysics, Bengaluru	Time domain astronomy	05 September 2019
Kamal Lodaya The Institute of Mathematical Sciences, Chennai	An afterword on foretelling	17 September 2019
Arnab Mukhopadhyay National Institute of Immunology, New Delhi	Living forever young – research to conquer aging	19 September 2019
Subir Sarkar University of Oxford, UK	Beyond the cosmological standard model	19 September 2019
CS Aravinda Tata Institute of Fundamental Research Bengaluru	Harish-Chandra - The mathematician and the artist	10 October 2019
John Philip Homi-Bhabha National Institute & Indira Gandhi Centre for Atomic Research Kalpakkam	Magnetic colloid: A wonderful model system with interesting applications	11 October 2019
Charles Lineweaver The Australian National University, Australia	Astrobiology, exoplanets and trying to answer the question: Are we alone in the universe?	15 October 2019
Charles Lineweaver The Australian National University, Australia	Noble Prize in Physics, 2019	16 October 2019
Tamal Sarkar Jawaharlal Nehru University, New Delhi	Kinetics of nanocomposite gels and electrochemical biosensing using iron oxide-carbon nanoparticles	23 October 2019
Chirag Kalelkar Indian Institute of Technology, Kharagpur	Stress banding in compressed quasi-two-dimensional aqueous foams	23 October 2019
Debarghya Banerjee Max Planck Institute for Dynamics and Self-Organization, Germany	Dynamics of topological defects in three dimensional active nematics	30 October 2019
Sujay Mate L'Institut de Recherche en Astrophysique et Planétologie, France	Pinning down the cosmic explosions with the SVOM mission	31 October 2019
Axel Brockmann National Centre for Biological Sciences, Bengaluru	Towards identifying molecular mechanism underlying advanced behavioral capabilities in insects	31 October 2019
Dominique G Homberger Louisiana State University, USA	Natural experiments and long-term eco-morphological studies: The evolutionary history of Gondwanan cockatoos and parrots	13 November 2019

Name	Title	Date
Christian Maes Katholieke Universiteit Leuven, Belgium	A possible nonequilibrium imprint in the cosmic background at low frequencies	22 November 2019
Vena Kapoor Nature Conservation Foundation, Bengaluru	Stupendous spiders - the weavers and stalkers amongst us	28 November 2019
Mansi S Kasliwal California Institute of Technology, USA	The dynamic infrared sky	12 December 2019
Lorenzo Pavesi University of Trento, Italy	Classical and quantum integrated silicon photonics	13 December 2019
Kshitij Thorat Rhodes University, South Africa	Bottling the genie: Capturing diffuse gases in extragalactic radio sources	19 December 2019
Priyamvada Natarajan Yale University, Connecticut	Unraveling the nature of supermassive black holes	20 December 2019
Igor Musevic University of Ljubljana, Slovenia	Topological defect formation in a nematic undergoing an extreme temperature quench	03 January 2020
Igor Musevic University of Ljubljana, Slovenia	Skyrmions in blue phase liquid crystals	06 January 2020
Niladri Sarkar Leiden University, Netherlands	Electrohydrodynamics of epithelial tissues	06 January 2020
Hridesh Kedia Massachusetts Institute of Technology, USA	Drive-specific adaptation in disordered mechanical networks of bistable springs	07 January 2020
Siddarth Joshi University of Bristol, UK	Advances in quantum communication networks: Many users & satellite links	07 January 2020
Buddhapriya Chakrabarti University Of Sheffield, UK	Wetting and surface migration in complex mixtures of polymers and gels	09 January 2020
Lorenzo Maccone Universita' di Pavia, Italy	Digital metrology	10 January 2020
Sayan Patra Vrije Universiteit, The Netherlands	Fundamental physics from molecular vibrations	13 January 2020
Sandeep Choubey Max Planck Institute for the Physics of Complex Systems, Germany	Regulatory asymmetry in the negative single-input module network motif	13 January 2020
Michael Berry University of Bristol, UK	Mirages and mirrors	16 January 2020
Pallavi Bhat University of Leeds, UK	Magnetic reconnection in laboratory and astrophysical plasmas	17 January 2020

Name	Title	Date
Peter Rohde University of Technology Sydney, Australia	The geopolitics of the quantum technology race	21 January 2020
Deepak Pandey University Bonn, Germany	Two-photon Raman processes in the cavity-QED based quantum technology	21 January 2020
Sasikumar Raja Observatoire de Paris, Paris	Solar wind density turbulence using Angular-broadening and interplanetary scintillation observations	27 January 2020
Sayantan Choudhury Max Planck Institute for Gravitational Physics Germany	Cosmology meets condensed matter physics	28 January 2020
Indira Chowdhury Srishti Institute of Art, Design and Technology Bengaluru	Science and the creation of an 'elsewhere': Bhabha's international network and research at the Tata Institute of Fundamental Research 1945-1966	30 January 2020
Aashima Dogra Life of Science Media Platform Delhi (Free Lance)	Science communication as a mirror to science (Annamani Lecture series)	30 January 2020
Ashok Mohapatra National Institute of Science Education and Research, Bhubaneswar	Dynamical phase transition in mirrorless optical parametric oscillator	10 February 2020
Suresh Varadarajan Raman Research Institute, Bengaluru	National Pension System	17 February 2020
Bhaskaran Muralidharan Indian Institute of Technology Bombay Maharashtra	Quantum transport in topological superconductor hybrid systems	18 February 2020
Nazma Islam NASA Goddard Space Flight Center, USA	An XMM-Newton + Chandra study of the hot gas in early type galaxies	18 February 2020
Suraka Bhattacharjee SN Bose National Centre for Basic Sciences West Bengal	Effective spin and charge couplings in doped quantum antiferromagnets	19 February 2020
Deepak Kallepalli University of Ottawa, Canada	Ultrafast laser desorption and ionization - applications	26 February 2020
Sanjukta Roy	Spin correlation spectroscopy in ultra-cold Bose-Fermi mixture	02 March 2020
Christian Maes Katholieke Universiteit Leuven, Belgium	Death and resurrection of a current	04 March 2020
Arnab Mukhopadhyay National Institute of Immunology, New Delhi	Living forever young - research to conquer aging	05 March 2020

Name	Title	Date
Santanu Kumar Pal Indian Institute of Science Education and Research, Mohali	Highly efficient Ambipolar charge transport in semiconducting discotic liquid crystals	11 March 2020

Quantum Frontiers & Fundamentals

13 January – 18 January 2020 Venue: Raman Research Institute, Bengaluru

Name & Institute/University	Title of the Talk
13 January 2020	
Harald Weinfurter Ludwig Maximilian University, Germany	From Bell tests to quantum network links
Archan S. Majumdar SN Bose National Centre for Basic Sciences, Kolkata	Semi-device-independent self-testing
Costantino Budroni Institute for Quantum Optics and Quantum Information, Austria	Nonclassical temporal correlations in systems with finite memory
Alok K Pan National Institute of Technology, Patna	Sharing non-trivial preparation contextuality by arbitrary number of sequential observers
Gregor Weihs University of Innsbruck, Austria	Multi-path and multi particle Interference
Saikat Ghosh Indian Institute of Technology, Kanpur	Quantum phase synchronization in spin 1 atoms
Simanraj Sadana Raman Research Institute, Bengaluru	Near-100% two-photon-like coincidence-visibility dip with classical light and the role of complementarity
Suraj Goel Indian Institute of Technology, Delhi	Unscrambling entanglement through a complex medium
Somshubhro Bandyopadhyay Bose Institute, Kolkata	Strong quantum nonlocality without entanglement
Ahana Ghoshal Harish-Chandra Research Institute, Allahabad	Coherence as witness for quantumness of gravity
Omkar Srikrishna Seoul National University Republic of Korea	Resource-efficient topological fault-tolerant quantum computation with hybrid entanglement of light

Name & Institute/University	Title of the Talk
Som Kanjilal Bose Institute, Kolkata	Optimal random access code and resource for quantum advantage
Ravikumar Chinnarasu National Tsing Hua University, Taiwan	Generation of sub-MHz bandwidth biphotons by controlled quantum interference
14 January 2020	
Anil Kumar Indian Institute of Science, Bengaluru	Quantum information processing by NMR: Interesting results from our laboratory
TS Mahesh Indian Institute of Science Education and Research Pune	Investigating quantum correlations through nuclear magnetic resonance
Adrian Kent University of Cambridge, UK	S-money: Virtual tokens for a relativistic economy
Sougato Bose University College London, UK	Table-top testing of the non-classicality of gravity: Assumptions
Piotr Kolenderski Nicolaus Copernicus University, Poland	Photons for micro and macro applications
Damián Pitalúa García University of Cambridge, United Kingdom	Practical quantum tokens without quantum memories: towards a proof-of-principle experimental demonstration
Stephan Sponar Atominstitut, Austria	Experimental studies of measurement uncertainty relations in neutron optics
Arun K Pati Harish-Chandra Research Institute, Allahabad	Weak value, modular value and potent value
Kasturi Saha Indian Institute of Technology Bombay, Mumbai	Magnetometry with color defects in diamond
Tabish Qureshi Jamia Millia Islamia University, New Delhi	Is there a momentum transfer in which-way measurement?
S Lakshmibala Indian Institute of Technology Madras, Chennai	Entanglement and squeezing properties of tripartite continuous variable systems
Sai Vinjanampathy Indian Institute of Technology Bombay, Mumbai	Preparations and weak-field phase control can witness initial correlations
Srikanth Radhakrishna Poornaprajna Institute of Scientific Research, Bengaluru	Convex combination of quantum channels
Noufal Jaseem P Indian Institute of Technology Bombay, Mumbai	Quantum synchronization in nano-scale heat engines

Name & Institute/University	Title of the Talk
Shounak Datta SN Bose National Centre for Basic Sciences, Kolkata	Anharmonicity can enhance the performance of quantum refrigerators
15 January 2020	
A Ravi P Rau Louisiana State University , USA	Using symmetries to understand and work with quantum correlations
Yutaka Shikano Keio University, Japan	Quantum random numbers in quantum computer
Antonio Acin The Institute of Photonic Sciences, Spain	Correlations in quantum networks
Indranil Chakrabarty International Institute of Information Technology Hyderabad	Broadcasting of correlations in quantum world
Perola Milman Paris Diderot University, France	Continuous variables error correction out of the box using SPDC
Kaushik Joarder Raman Research Institute, Bengaluru	Simulation and experimental demonstration of single-photon based QKD (B92) protocol
Souradeep Sasmal Bose Institute, Kolkata	A generic scheme for enhancing randomness towards maximum amount of Bell-CHSH certified genuine randomness
Prasanta K Panigrahi Indian Institute of Science Education and Research Kolkata	Quantum photons from a diplole coupled two-level atomic system
Ujjwal Sen Harish-Chandra Research Institute, Allahabad	Entanglement and related concepts in glassy quantum systems
Anil Shaji Indian Institute of Science Education and Research Thiruvananthapuram	Initial correlations in photonic dephasing dynamics
Ravindra Pratap Singh Physical Research Laboratory, Ahmedabad	Duality in entanglement: Polarization and orbital angular momentum of photons
Yves Caudano University of Namur, Belgium	Using the Majorana representation and weak measurements to investigate quantum paradoxes
Ashok Kumar Indian Institute of Space Science and Technology Thiruvananthapuram	Quantum-enhanced sensing for plasmonic sensors
Devashish Tupkary Indian Institute of Science, Bengaluru	Towards a device-independent witness of tripartite entanglement resource

Name & Institute/University	Title of the Talk
16 January 2020	
Sibasish Ghosh The Institute of Mathematical Sciences, Chennai	Measurement based quantum heat engine with coupled working medium
Arindam Ghosh Indian Institute of Science, Bengaluru	Thermoelectricity in twisted bilayer grapheme
Sherilyn Wright Cambridge Quantum Computing, UK	Towards device-independent randomness amplification
Reena Dayal Yadav Microsoft, India	Effect in quantum inspired algorithms
Apoorva Patel Indian Institute of Science, Bengaluru	Understanding the born rule in weak quantum measurements
Debasis Sarkar University of Calcutta, Kolkata	Quantum correlations in quantum network scenario
Arul Lakshminarayan Indian Institute of Technology Madras, Chennai	Creating maximally entangled and entangling quantum evolutions
Suchetana Goswami SN Bose National Centre for Basic Sciences, Kolkata	Protecting quantum correlations in presence of generalised amplitude damping channel: the two-qubit case
Swati Kumari Bose Institute, Kolkata	Macrorealistic inequalities stronger than the standard Leggett-Garg inequalities
Shiladitya Mal Harish-Chandra Research Institute, Allahabad	Witnessing bipartite entanglement sequentially by multiple observers
Debarshi Das Bose Institute, Kolkata	Persistence of quantum violation of macrorealism for large spins even under coarsening of measurement times
17 January 2020	
AR Usha Devi Bangalore University, Bengaluru	Violation of Leggett-Garg inequality under non-hermitian PT symmetric Hamiltonian evolution
Rajamani Vijayaraghavan Tata Institute of Fundamental Research, Mumbai	High fidelity measurements in superconducting qubits
Lorenzo Maccone Universita' di Pavia, Italy	Quantum time and time of arrival
Manabendra Nath Bera Indian Institute of Science Education and Research Mohali	The second laws for quantum and nano-scale heat engines

Name & Institute/University	Title of the Talk
Siddhant Das Ludwig-Maximilians-Universitat Munchen, Germany	Arrival time distributions and spin in quantum mechanics: A Bohmian perspective
Alex Matzkin Centre national de la recherche scientifique, France	Weak values from path integrals
Surya N Sahoo Raman Research Institute, Bengaluru	Measuring average of non-Hermitian operator with weak value in a Mach-Zehnder interferometer
Cyril Branciard Institut NEEL- Centre national de la recherche scientifique, France	Quantum circuits with classical versus quantum control of causal orders
Ashutosh Singh Raman Research Institute, Bengaluru	Manipulation of entanglement sudden death in an all-optical experimental setup
18 January 2020	
Jian-Wei Pan University of Science and Technology, China	Quantum science experiments in space
Thomas Jennewein Institute for Quantum Computing, Canada	Novel techniques for ground-to-space quantum channels (VC)
Khabat Heshami University of Ottawa, Canada	Quantum communication over global distances (VC)
Feihu Xu University of Science and Technology, China	A low-cost quantum network with untrusted relay over fiber
Konrad Banaszek University of Warsaw, Poland	From quantum information science to deep-space optical communication
Xiao-Bo Zhu University of Science and Technology, China	Progress on superconducting multi-qubit system
Peter Rohde University of Technology Sydney, Australia	Entanglement routing in the quantum internet - exploiting the differences between classical and quantum data
R Umamaheshwaran Indian Space Research Organization, Bengaluru	The importance of quantum communications in India's space programme
Urbasi Sinha Raman Research Institute, Bengaluru	Quantum Communication at RRI Bangalore

Visitors

Appendix - IV

Sl. No	Name and Institution	Duration of Stay
1	Asha K Kuvempu University, Shimoga	05 - 30 April 2019 16 – 18 May 2019 30 September - 12 October 2019
2	Apurva Oza University of Bern, Switzerland	07 – 08 April 2019
3	Kalyani Bagri Pt. Ravishankar Shukla University, Raipur	15 – 18 April 2019
4	Anoop K K Cochin University of Science & Technology, Kerala	07 May – 30 June 2019
5	Muhammed Shafi Ollakkan Pocker Sahib Memorial Orphanage College, Kerala	08 – 17 May 2019
6	Dipankar Home Bose Institute, Kolkata	11 – 16 May 2019 25 - 29 June 2019 30 October – 03 November 2019 11 – 21 January 2020
7	Sumanth Indian Institute of Technology, Kharagpur	15 May - 15 July 2019
8	Ishwara Chandra National Centre for Radio Astrophysics, Pune	22 - 25 May 2019
9	Balu Sreedhar Pondicherry University, Pondicherry	22 – 25 May 2019
10	Fabien Bretenaker CNRS Laboratoire Aime Cotton, France	23 May – 06 June 2019 09 – 17 December 2019
11	Ajay Kumar Indian Navy, Cochin	25 May – 02 June 2019 09 – 18 January 2020
12	PK Mohanty Saha Institute of Nuclear Physics, Kolkata	26 – 30 May 2019
13	Ujjwal Sen Harish Chandra Research Institute, Allahabad	27 May – 01 June 2019
14	Ann Mary St. Thomas College, Trichur	28 - 29 May 2019
15	Vivek Venkatraman Krishnan Max-Planck Institute for Radio Astronomy, Germany	10 – 14 June 2019

Sl. No	Name and Institution	Duration of Stay
16	Atul Ghalame University of Manchester, UK	10 – 18 June 2019
17	Tapomoy Guha Sarkar Birla Institute of Technology & Science, Pilani	13 – 17 June 2019
18	Ayyappan J Government College of Engineering, Thanjavur	15 – 16 June 2019 05 – 08 October 2019
19	Anmol Raina University of Illinois, USA	15 June – 15 August 2019
20	Sayantan Choudhury Max-Planck Institute for Gravitational Physics, Germany	17 – 24 June 2019
21	Arijit Sharma Indian Institute of Technology, Tirupati	18 June – 10 July 2019
22	Jagadeep Pandian Indian Institute of Space Science and Technology Thiruvananthapuram	25 – 27 June 2019
23	Prantik Chakraborty Space Applications Centre, Ahmedabad	26 – 27 June 2019 09 – 11 January 2020
24	Tom Lubensky University of Pennsylvania, USA	04 – 06 July 2019
25	AV Radhakrishnan Université de Bordeaux, France	05 July – 11 September 2019
26	Nirmal Kumar Iyer KTH Royal Institute of Technology, Sweden	08 – 13 July 2019
27	Sonali Sachdeva Kavli Institute for Astronomy & Astrophysics, China	15 – 22 July 2019
28	Krishnapriya SR Okinawa Institute of Science and Technology, Japan	22 July 2019
29	Yashwant Gupta National Centre for Radio Astrophysics, Pune	28 – 30 July 2019
30	Philip Diamond Square Kilometer Array Organisation, UK	30 July 2019
31	Shauri Chakraborty SN Bose National Centre for Basic Sciences, Kolkata	19 – 20 August 2019
32	Shahnawaz Malik University of Kashmir, Srinagar	01 September – 30 November 2019

Sl. No	Name and Institution	Duration of Stay
33	John Philip Indira Gandhi Centre for Atomic Research, Kalpakkam	10 – 13 October 2019
34	Debashis Saha Center for Theoretical Physics, Poland	15 – 18 October 2019
35	Charles Lineweaver Australian National University, Australia	16 October 2019
36	Chirag Kalelkar Indian Institute of Technology, Kharagpur	22 – 23 October 2019
37	Nishant Kumar Singh Inter-University Centre for Astronomy & Astrophysics, Pune	24 October –01 November 2019
38	Naomi McClure-Griffiths Australian National University, Australia	28 October – 01 November 2019
39	Peter Quinn The International Centre for Radio Astronomy Research, Australia	28 October – 01 November 2019
40	Justin Leonard Jonas Rhodes University, South Africa	29 – 31 October 2019
41	Anotonio Chrysostomou Square Kilometer Array Organisation, UK	29 – 31 October 2019
42	Luca Stringhetti Square Kilometer Array Organisation, UK	29 – 31 October 2019
43	Robert Braun Square Kilometer Array Organisation, UK	29 – 31 October 2019
44	Philip Diamond Square Kilometer Array Organisation, UK	29 – 31 October 2019
45	Andrea Ferrara Scoula Normale Superiore, Italy	29 October – 01 November 2019
46	Adrian Paul Grenville Russell ESO-European Organisation for Astronomical Research, Germany	29 October – 02 November 2019
47	Brian Ernest Glendenning National Radio Astronomy Observatory, USA	29 October – 02 November 2019
48	Sujay Mate Institut de Recherche en Astrophysique et Planétologie, France	30 October – 02 November 2019
49	Matthias Steinmetz Leibniz-Institut fuer Astrophysik, Germany	30 October –02 November 2019

Sl. No	Name and Institution	Duration of Stay
50	Catherine Cesarsky Square Kilometer Array Organisation, UK	30 October – 02 November 2019
51	Lewis Timothy Ball Square Kilometer Array Organisation, UK	30 October – 02 November 2019
52	A Ravi P Rau Louisiana State University, USA	03 November – 02 December 2019 12 -14 December 2019
53	Dhiraj K Dedhia Tata Institute of Fundamental Research, Mumbai	10 – 20 November 2019 01 – 10 January 2020
54	Raste Janakee Dhirajlal Tata Institute of Fundamental Research, Mumbai	13 – 22 November 2019
55	Girish Kulkarni Tata Institute of Fundamental Research, Mumbai	14 – 16 November 2019
56	Satya Majumdar Laboratory of Theoretical Physics & Statistical Models, France	18 November –21 December 2019
57	Christian Maes Institute for Theoretical Physics, Belgium	22 – 24 November 2019 27 February - 15 March 2020
58	Mansi S Kasliwal California Institute of Technology, USA	12 December 2019
59	Lorenzo Pavesi University of Trento, Italy	13 – 14 December 2019
60	Igor Musevic University of Ljubljana, Slovenia	16 December 2019 –19 January 2020
61	Kshitij Thorat Rhodes University, South Africa	18 – 20 December 2019
62	VPN Nampoori Cochin University of Science and Technology, Kerala	27 – 28 December 2019
63	Niladri Sarkar Leiden University, The Netherlands	6 January 2020
64	Deepak Pandey University Bonn, Germany	06 – 22 January 2020
65	Siddarth Joshi University of Bristol, UK	07 January 2020
66	Pallavi Bhat University of Leeds, UK	09 January 2020

Sl. No	Name and Institution	Duration of Stay
67	Gopakumar Tata Institute of Fundamental Research, Mumbai	09 - 11 January 2020
68	Tuhin Ghosh National Institute of Science Education and Research Bhubaneswar	09 – 11 January 2020
69	Jagadheep Pandian Indian Institute of Space Science and Technology Thiruvananthapuram	09 – 11 January 2020
70	Lokesh Kumar Dewangan Physical Research Laboratory, Ahmedabad	09 – 11 January 2020
71	Manoj Puravankar Tata Institute of Fundamental Research, Mumbai	09 – 11 January 2020
72	Sarita Vig Indian Institute of Space Science and Technology Thiruvananthapuram	09 – 12 January 2020
73	Amitesh Omar Aryabhata Research Institute of Observational Sciences, Nainital	09 – 12 January 2020
74	TK Sridharan Harvard-Smithosonian Center for Astrophysics, USA	09 – 20 January 2020
75	Bhaswati Mookerjea Tata Institute of Fundamental Research, Mumbai	10 – 11 January 2020
76	Sunder Sahayanathan Bhabha Atomic Research Centre, Mumbai	10 - 11 January 2020
77	Nirupam Roy Indian Institute of Science, Bengaluru	10 – 11 January 2020
78	Sivarani Thirupathi Indian Institute of Astrophysics, Bengaluru	10 – 11 January2020
79	Anupama GC Indian Institute of Astrophysics, Bengaluru	10 – 11 January 2020
80	Girish V Indian Space Research Organisation, Bengaluru	10 – 11 January 2020
81	Sreekumar P Indian Space Research Organisation, Bengaluru	10 – 11 January 2020
82	Pravabati Chingangbam Indian Institute of Astrophysics, Bengaluru	10 – 11 January 2020

Sl. No	Name and Institution	Duration of Stay
83	Abhirup Datta Indian Institute of Technology, Indore	10 – 12 January 2020
84	Sandeep Choubey Max Planck Institute for the Physics of Complex Systems, Germany	12 – 15 January 2020
85	Michael Berry University of Bristol, UK	16 - 20 January 2020
86	Sasikumar Raja Observatoire de Paris, France	20 – 29 January 2020
87	AP Balachandran Syracuse University, New York	25 January –4 February 2020
88	Sayantan Choudhury Max Planck Institute for Gravitational Physics, Germany	28 – 31 January 2020
89	Aashima Dogra Life of Science Media Flatform, Delhi (Freelance)	28 January – 06 February 2020
90	Karamveer Kaur Hebrew University of Jerusalem, Israel	29 January – 02 February 2020
91	Jeewan Pandey Aryabhata Research Institute of Observational Sciences, Nainital	06 - 08 February 2020
92	Ashok Mohapatra National Institute of Science Education and Research, Bhubaneswar	09 - 11 February 2020
93	Nilanjan Bondyopadhyaya Viswabharati University, West Bengal	11 – 22 February 2020
94	Smijesh Nadarajan Mahatma Gandhi University, Kottayam	15 – 17 February 2020
95	Nazma Islam Goddard Space Flight Center, USA	17 – 20 February 2020
96	Bhaskaran Muralidharan Indian Institute of Technology-Bombay, Mumbai	18 February 2020
97	Suraka Bhattacharjee SN Bose National Centre for Basic Sciences, Kolkata	18 – 26 February 2020
98	Anindya Sundar Paul Technion University, Israel	24 February – 10 March 2020
99	Deepak Kallepalli University of Ottawa, Canada	26 February 2020

Sl. No	Name and Institution	Duration of Stay
100	Rafael D Sorkin Perimeter Institute for Theoretical Physics, Canada	1 – 31 March 2020
101	Arnab Mukhopadhyay National Institute of Immunology, New Delhi	4 – 5 March 2020
102	Santanu Kumar Pal Indian Institute of Science Education and Research, Mohali	07 – 12 March 2020
103	Subhabrata Majumdar Tata Institute of Fundamental Research, Mumbai	15 – 17 March 2020

RRI Science Forum

Appendix - V

Sl. No	Discussed by	Paper Discussed	Date
1	Nomaan	The hierarchical view of Mathematics	11 April 2019
2	Raghunathan A	Searching for out-of-band information within the band?	25 April 2019
3	Santanu Das	Exploitation-exploration tradeoff in searching	09 May 2019
4	Avinash Deshpande	Universality of free fall from the orbital motion of a pulsar in a stellar triple system	27 June 2019
5	Prabu T	Quantum machine learning	25 July 2019
6	Nayantara Gupta	Cosmic positron excess	26 September 2019
7	Joseph Samuel	The enduring mystery of Ettore Majorana and his elusive Particles	03 October 2019
8	Biswajit Paul	Discovery of a very young high-mass X-ray binary associated with the supernova remnant	24 October 2019
9	Sayantan Majumdar	Tuning dissipation in dense suspension flows by random organization	14 November 2019
10	Supurna Sinha	Ultradilute quantum droplets	21 November 2019
11	Sadiq Rangwala	Does the electron have an electric dipole moment?	27 February 2020
12	Narendra Nath Patra	Vertical structure of galaxies: A powerful tool to probe many physics	12 March 2020

Visiting Students' Programme

Appendix - VI

Mentor	Students	
Prabu T	Abhishek R	Rachna M
	Arul Pandian	Sahana Bhattramakki
	Diwakar K	Shashank S Bhat
Hema Ramachandran	Agneya V D	Karthik B S
	Bindushree M	Shashank Kumar
	Chandrika Avvaru	Vasuki M
	Gayatri Reshma Sasidharan	Vishnupriya P V
Ramesh B	Aishwarya R	
	Pinaki Roy	
	Rishikesh Dudhat	
Reji Philip	Aji Alexander	
	Amogh M S	
	Gopika Anil	
	Sumi Thomas	
Raghunathan A	Akash V Kulkarni	
	Kavitha K	
Deshpande AA	Albert Shaji	Reshma Reba Alexander
	Devansh Shukla	Saurabh Kumar
	Eshika Chittora	Vidya B
	Pavan U A	Yash Bhusare
Sumati Surya	Anup Anand Singh	
Saptarishi Chaudhuri	Archana Mehta	Nikitha Kuntimaddi
	G L Priyanka	Varghese Alapatt
	Mahesh K N B	
Pratibha R	Arkalekha Neogi	
	Sharadhi N Raj	
Ravi Subrahmanyan	Balu Sreedhar	
	Samskruti Ganjam	
Girish BS	Balu Sreedhar	
Sayantan Majumdar	Chinmayee Wamorkar	Shibil Adam Kunikkadan
	Firoz M K	Subhransu Dhar
	Neil Ashwin Raj	Vaisakh V
	Raju Sarkar	Vibha Balaji
	Sai Harshitha S	Vinay Anand
Urna Basu	Christy Pius	
	Onkar Ravindra Sadekar	
	Romesh Srivastava	
	Vijaya Kumar	

Mentor	Students	
Sandeep Kumar	Femi Rose Tharakan Najiya Priyanka Kumari Rashmi R Naik Shaina Mathew K S Shikha Singh	Sreelakshmi V Suraksha Swasthika Tejaswini S Rao Tripti Agnihotri
Sridhar S	Gayathri C	
Gautam Soni	Jyoti Sharma Pruthvi M	
Biswait Paul	Ketan Rikame	
Pramod Pullarkat	Kshitija Joshi Lakshmi N G Pramit Bandyopadhyay Shrinivas Jayaram	
Andal Narayanan	Mohammed Zia Saswath J K	
Dibyendu Roy	Monira Fatma Sai Sheshank Bandaru Vedant Kashyap	
Ranjini Bandyopadhyay	Nizzy Peter Shifana Lourdes K	
Arun Roy	Priyanka Kumari Smritee Rekha Hazarika	
Biman Nath	Pushpita Das	
Srivani KS	Rohith Kalyan V	
Joseph Samuel	Shivan Khullar	
Vikram Rana	Suhasini S Rao	
Vijayaraghavan D	Thejas R	

RAMAN RESEARCH INSTITUTE

Audited Statement of Accounts
2019-2020

GRSM & ASSOCIATES
Chartered Accountants

No. 8/90, 1st Floor, Pampa Mahakavi Road,
Shankarapuram, Bangalore-560 004.
Ph : +91-80-41312149 / +91-80-2660 2810

INDEPENDENT AUDITOR'S REPORT

To
Members of Raman Research Institute

Opinion

We have audited the accompanying financial statements of **M/s Raman Research Institute, ("Institute"),** Sir C V Raman Avenue, Sadashivanagar, Bangalore 560080, which comprises of the balance sheet as at March 31st 2020, the Income & Expenditure Account for the year then ended, the Receipts and Payment Account for the year then ended, and notes to the financial statements, including a summary of significant accounting policies.

In our opinion and to the best of our information and according to the explanations given to us, except for the effects of the matter described in the Basis for Opinion section of our report, the accompanying financial statements give a true and fair view of the financial position of the Institute as at March 31, 2020, and of its financial performance and its receipts and payments for the year then ended in accordance with the Accounting Standards issued by the Institute of Chartered Accountants of India (ICAI).

Basis for Opinion

We conducted our audit in accordance with the Standards on Auditing (SAs) issued by ICAI. Our responsibilities under those standards are further described in the Auditor's Responsibilities for the Audit of the Financial Statements section of our report. We are independent of the Institute in accordance with the Code of Ethics issued by ICAI and we have fulfilled our other ethical responsibilities in accordance with the Code of Ethics. We believe that the audit evidence we have obtained is sufficient and appropriate to provide a basis for our opinion.

Responsibilities of Management and Those Charged with Governance for the Financial Statements.

Institute's Management is responsible for the preparation of these financial statements that give a true and fair view of the state of affairs, results of operations and receipts and payments of the Institute in accordance with the accounting principles generally accepted in India. This responsibility includes the design, implementation, and maintenance of internal control relevant to the preparation and presentation of the financial statements that give a true and fair view and are free from material misstatement, whether due to fraud or error.

In preparing the financial statements, the Institute's management is responsible for assessing its ability to continue as a going concern, disclosing, as applicable, matters

related to going concern and using the going concern basis of accounting unless management either intends to liquidate the Institute or to cease operations, or has no realistic alternative but to do so.

Those charged with governance are responsible for overseeing the Institute's financial reporting process.

Auditor's Responsibilities for the Audit of the Financial Statements

Our objectives are to obtain reasonable assurance about whether the financial statements as a whole are free from material misstatement, whether due to fraud or error, and to issue an auditor's report that includes our opinion. Reasonable assurance is a high level of assurance but is not a guarantee that an audit conducted in accordance with SAs will always detect a material misstatement when it exists. Misstatements can arise from fraud or error and are considered material if, individually or in the aggregate, they could reasonably be expected to influence the economic decisions of users taken on the basis of these financial statements.
As part of an audit in accordance with SAs, we exercise professional judgment and maintain professional skepticism throughout the audit. We also:

- Identify and assess the risks of material misstatement of the financial statements, whether due to fraud or error, design and perform audit procedures responsive to those risks, and obtain audit evidence that is sufficient and appropriate to provide a basis for our opinion. The risk of not detecting a material misstatement resulting from fraud is higher than for one resulting from error, as fraud may involve collusion, forgery, intentional omissions, misrepresentations, or the override of internal control.
- Obtain an understanding of internal control relevant to the audit in order to design audit procedures that are appropriate in the circumstances, but not for the purpose of expressing an opinion on the effectiveness of the Institute's internal control.
- Evaluate the appropriateness of accounting policies used and the reasonableness of accounting estimates and related disclosures made by management.
- Conclude on the appropriateness of management's use of the going concern basis of accounting and, based on the audit evidence obtained, whether a material uncertainty exists related to events or conditions that may cast significant doubt on the Institute's ability to continue as a going concern. If we conclude that a material uncertainty exists, we are required to draw attention in our auditor's report to the related disclosures in the financial statements or, if such disclosures are inadequate, to modify our opinion. Our conclusions are based on the audit evidence obtained up to the date of our auditor's report. However, future events or conditions may cause the Institute to cease to continue as a going concern.

We communicate with those charged with governance regarding, among other matters, the planned scope and timing of the audit and significant audit findings, including any significant deficiencies in internal control that we identify during our audit.

We also provide those charged with governance with a statement that we have complied with relevant ethical requirements regarding independence, and to communicate with them all relationships and other matters that may reasonably be thought to bear on our independence, and where applicable, related safeguards.

For GRSM & ASSOCIATES
Chartered Accountants
FRN: 000863S

GRSM & ASSOCIATES Bangalore Chartered Accountants

GOPALKRISHNA HEGDE
M.No.208063
Partner
UDIN: 20208063AAAAFJ3765

Place: Bangalore
Date: 7th July 2020

RAMAN RESEARCH INSTITUTE, BENGALURU

BALANCE SHEET AS AT 31ST MARCH 2020

(Amount in INR)

CORPUS/CAPITAL FUND AND LIABILITIES	Schedule	Current Year	Previous Year
Corpus/Capital Fund	1	103,71,86,702	105,60,91,329
Reserves & Surplus	2	-	-
Earmarked & Endowment Funds	3	63,54,52,816	67,09,33,875
Secured Loans & Borrowings	4	-	-
Unsecured Loans & Borrowings	5	-	-
Deferred Credit Liabilities	6	-	-
Current Liabilities & Provisions	7	1,91,29,454	2,33,87,719
TOTAL		**169,17,68,972**	**175,04,12,923**
ASSETS			
Fixed Assets	8	90,04,21,237	92,31,35,873
Investments- from earmarked & endowment funds	9	59,32,17,739	65,99,47,147
Investments-Others	10	1,00,00,000	1,00,00,000
Current Assets, Loans & Advances	11	18,81,29,996	15,73,29,903
TOTAL		**169,17,68,972**	**175,04,12,923**
Significant Accounting Policies	24		
Contingent Liabilities and Notes on Accounts	25		

As per our report of even date
for M/s GRSM & ASSOCIATES
Chartered Accountants
FRN 000863S

Sd/-
(Naresh V. S)
Administrative Officer (i/c)

Sd/-
(Ravi Subrahmanyan)
Director

Sd/-
(Gopalkrishna Hegde)
Partner
M No. 208063

BENGALURU / 7th July 2020

RAMAN RESEARCH INSTITUTE, BENGALURU

INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR ENDED 31ST MARCH 2020

(Amount in INR)

INCOME	Schedule	Current Year	Previous Year
Income from Sales/Services	12	-	-
Grants/Subsidies	13	53,61,59,736	50,87,81,568
Fee/Subscriptions	14	-	-
Income from Investments for earmarked/endowment funds)	15	-	-
Income from Royalty	16	-	-
Interest Earned	17	75,46,893	84,62,017
Other Income	18	76,75,314	67,60,017
Increase/Decrease in stock of finished goods	19	-	-
TOTAL (A)		**55,13,81,943**	**52,40,03,602**
EXPENDITURE			
Establishment Expenses	20	34,72,24,885	31,78,54,433
Other Administrative Expenses	21	13,65,76,398	12,97,96,369
Expendtiture on Grants/Subsidies	22	-	-
Interest	23	-	-
Depreciation (Net as per Schedule 8)		6,73,63,736	6,51,86,568
TOTAL (B)		**55,11,65,019**	**51,28,37,370**
INTEREST ON GRANT BALANCES TRF TO BHARATKOSH - Sch 7(A)(1b)		**17,85,815**	**22,82,539**
BALANCE-SURPLUS/(DEFICIT) CARRIED TO CORPUS/CAPITAL FUND - Sch. 1(2b)		**(15,68,891)**	**88,83,693**
Significant Accounting Policies	24		
Contingent Liabilities and Notes on Accounts	25		

As per our report of even date
for M/s GRSM & ASSOCIATES
Chartered Accountants
FRN 000863S

Sd/-
(Naresh V. S)
Administrative Officer (i/c)

Sd/-
(Ravi Subrahmanyan)
Director

Sd/-
(Gopalkrishna Hegde)
Partner
M No. 208063

BENGALURU / 7th July 2020

RAMAN RESEARCH INSTITUTE, BENGALURU
RECEIPTS AND PAYMENTS STATEMENT FOR THE YEAR ENDED 31ST MARCH 2020

(Amount in INR)

RECEIPTS	Current Year	Previous Year	PAYMENTS	Current Year	Previous Year
I. Opening Balances			**I. Expenses**		
a) Cash in hand	281	-	a) Establishment Exp	34,72,24,885	31,78,54,433
b) Bank Balances	1,81,70,199	2,37,06,854	b) Admin Expenses	13,65,77,037	12,84,72,101
c) Deposits	33,06,96,492	25,57,33,900	c) PF-Final Settlement	3,11,61,685	78,97,135
d) Stamps (Franking M/C)	14,407	966	d) Pension Payout	-	-
II. Grants Received			**II. Payments made against projects**	6,09,77,259	2,68,16,173
a) From Govt. of India	51,88,24,000	48,81,60,000			
b) From State Govt.	-	-	**III. Investment and deposits made**		
c) From other sources	6,92,03,040	8,61,87,555	a) Out of earmarked funds	-	-
			b) Out of own funds (investment-others)	-	-
III. Income on Investments from					
a) Earmarked & Endowment Funds	-	-	**IV. Expenditure on Fixed Assets & CWIP**	5,51,50,309	4,22,88,842
b) Own Funds	-	-			
			V. Refund of surplus money / loans		
IV. Interest Received			a) To Govt. of India	-	-
a) On Bank deposits	2,28,58,106	2,20,56,391	b) To State Govt	-	-
b) on Loans, Advances etc.	1,26,229	3,02,272	c) To other fund providers	-	-
V. Other Income (Specify)	77,24,073	70,46,848	**VI. Finance charge (Interest)**	-	-
VI. Amount Borrowed	1,53,975	-	**VII. Other Payments (Specify)**	-	-
VII. Any other Receipts (Specify)			a) TDS Receivable	14,49,366	8,42,890
a) Advances	3,88,42,932	20,18,400	b) Advances	4,79,84,183	25,25,734
b) Receivables	1,08,84,624	1,69,10,881	c) Investments (Nett)	28,10,770	-
c) Accrued Interest	1,72,485	10,94,118	d) EMD, SD, CD (Deposits)	19,92,679	12,57,184
d) Investments (Nett)	1,13,09,400	37,912	e) Bills Payable	1,75,94,585	29,36,010
e) Overheads	29,70,661	4,65,320	f) Payroll Recoveries	5,35,62,615	3,14,66,711
f) Deposits	7,40,000	8,40,000	g) Deposits (for services)	-	-
g) Pension Corpus	2,95,00,000	35,71,204	h) Duties & Taxes	15,55,883	13,41,016
h) Employees's subscription	1,88,55,710	1,80,01,300	i) Provision	11,66,059	13,11,739
			j) PF-Withdrawals	1,09,01,000	94,93,000

RAMAN RESEARCH INSTITUTE, BENGALURU
RECEIPTS AND PAYMENTS STATEMENT FOR THE YEAR ENDED 31ST MARCH 2020

(Amount in INR)

RECEIPTS	Current Year	Previous Year	PAYMENTS	Current Year	Previous Year
			h) CPF (Emplyr Share)-Trf to Pension	2,95,00,000	27,49,573
			VIII. Closing Balances		
			a) Cash Balance	300	281
			b) Bank Balances		
			i) Deposit Accounts	23,98,76,801	33,06,96,492
			II) Current/Savings Account	4,15,52,578	1,81,70,200
			c) Postal franking machine	8,620	14,407
TOTAL	**108,10,46,614**	**92,61,33,921**		**108,10,46,614**	**92,61,33,921**

- -

As per our report of even date
for M/s GRSM & ASSOCIATES
Chartered Accountants
FRN 000863S

Sd/-
(Naresh V. S)
Administrative Officer (i/c)

Sd/-
(Ravi Subrahmanyan)
Director

Sd/-
(Gopalkrishna Hegde)
Partner
M No. 208063

BENGALURU / 7th July 2020

RAMAN RESEARCH INSTITUTE, BENGALURU

SCHEDULES FORMING PART OF BALANCE SHEET AS AT 31ST MARCH 2020

(Amount in INR)

Schedule 1- Corpus/Capital Fund	Current Year		Previous Year	
(1) CAPITAL FUND REPRESENTING ASSETS CREATED OUT OF GRANTS				
As per last account	105,17,30,168		107,46,27,894	
Addition during the year	9,68,79,779		11,66,83,147	
Less: Deductions during the year *(Includes Capital Work-in-progress)*	4,17,29,470		7,43,94,305	
Less: Depreciation chargeable transferred to Income and Expenditure A/c	6,73,63,736		6,51,86,568	
BALANCE AS AT THE YEAR END		103,95,16,741		105,17,30,168
(2) GRANT BALANCES				
(a) NON-RECURRING GRANT				
Balance as at the beginning of the year		58,71,925		35,95,767
Add: Contributions during the year		5,00,28,000		4,45,65,000
Less: Expenditure incurred during the year		5,51,50,309		4,22,88,842
BALANCE AS AT THE YEAR END		7,49,616		58,71,925
(b) RECURRING GRANT				
Balance as at the beginning of the year	(15,10,764)		(1,03,94,457)	
Transferred from Income & Expenditure-	(15,68,891)		88,83,693	
-Account for the year				
BALANCE AS AT THE YEAR END		(30,79,655)		(15,10,764)
TOTAL (1+2)		**103,71,86,702**		**105,60,91,329**

Schedule-2- Reserves & Surplus	Current Year		Previous Year	
NOT APPLICABLE		-		-
TOTAL		**-**		**-**

RAMAN RESEARCH INSTITUTE, BENGALURU
SCHEDULES FORMING PART OF BALANCE SHEET AS AT 31ST MARCH 2020

Schedule 3- Earmarked/Endowment Funds

(Amount in INR)

Sl No	Funding Agency	Project Name	Opening Balance	Additions during the year	Utilisation			Total Utilisation	Balance as on 31/03/20
					Capital Expenditure	Recurring Expenditure	Advances/ Receivables		
Funded by Government Agencies									
1	DAE	Prof. Krishnakumar-RRF-DAE	4,79,032	12,00,000	-	15,37,747	-	15,37,747	1,41,285
2	CSIR	SSB Fellowship-Dr. Sadiq	-	1,80,000	-	-	-	-	1,80,000
3		SSB Fellowship-Prof Avinash Deshpande	-	1,50,000	-	-	-	-	1,50,000
4	DBT	Biomechanics of Synaptogesis-Dr Pramod	7,321	-	-	7,321	-	7,321	-
5		Joint Project-Dr. Pramod	1,66,763	-	-	3,51,987	-	3,51,987	(1,85,224)
6		DBT-BDTD Grant-Dr. Gautam	-	33,14,816	-	2,92,256	-	2,92,256	30,22,560
7		Ramalingaswamy Fellowship- Dr. Gautam	(18,142)	-	-	(18,142)	-	(18,142)	-
8	DST	DST-MWA Project- Prof Shiv Sethi	36,269	-	-	36,269	-	36,269	-
9		Ramanujan Fellowship- Dr Pramod	2,06,447	-	-	-	-	-	2,06,447
10		Indo-Aus BMWF Jt. Research	70,579	-	-	70,579	-	70,579	-
11		Indo-Aus Strategic Res. Fund- Dr Reji	(4,820)	-	-	(4,820)	-	(4,820)	-
12		DST-Indo-Russia-P/270-Prof Biman	2,50,000	-	-	-	-	-	2,50,000
13		DST-Indo-Russia-P/276-Prof Shiv	2,32,600	-	-	-	-	-	2,32,600
14		DST-QuST grant-Prof Urbasi	-	54,50,000	30,52,313	2,18,440	-	32,70,753	21,79,247
15		DST-Indo-Russia-Prof. Sandeep	-	14,90,400	-	80,000	-	80,000	14,10,400
16		DST-IndoItaly-Dr. Urbasi	53,58,200	4,61,016	-	6,57,669	-	6,57,669	51,61,547
17	IFCPAR	CEFIPRA Grant- Prof Hema R	1,37,525	-	-	-	-	-	1,37,525
18		CEFIPRA Grant- Dr. Sadiq Rangwala	(1,86,651)	7,84,000	-	5,17,482	-	5,17,482	79,867
19	ISRO	PRATUSH-Dr. Mayuri	36,00,000	-	2,58,300	14,91,376	-	17,49,676	18,50,324
20		ISRO-Polix Payload-Prof Biswajit	2,73,49,786	-	-	1,52,13,744	-	1,52,13,744	1,21,36,042
21		ISRO-QKD-Project-Dr. Urbasi	5,15,14,044	3,07,56,265	1,90,55,501	1,25,00,178	(11,34,932)	3,04,20,747	5,18,49,562
22	IUSSTF	IUSSTF Grant-Prof Shiv	5,02,580	33,809	-	5,36,389	-	5,36,389	-
23	SERB	Ramanujan Fellowship- Dr Sayantan	(3,144)	-	-	7,38,623	-	7,38,623	(7,41,767)
24		TARE Grant- Dr. Anoop, CUSAT	3,35,000	-	-	1,05,368	-	1,05,368	2,29,632
25		Ramanujan Fellowship- Dr Urna Basu	5,99,927	-	-	5,11,211	-	5,11,211	88,716
26		Vajra Fellowship-Prof Satya Majumdar	6,463	6,20,043	-	6,42,389	-	6,42,389	(15,883)
27		SERB Grant-Dr. Ranjini	-	23,96,500	16,63,315	3,77,247	-	20,40,562	3,55,938
28		Vajra Fellowship-Prof Sanders	1,10,330	-	-	2,91,826	-	2,91,826	(1,81,496)
29	SERB	Ramanujan Fellowship-Dr. Dibyendu	9,91,531	4,00,000	-	9,29,938	-	9,29,938	4,61,593

Schedule 3- Earmarked/Endowment Funds

(Amount in INR)

Sl No	Funding Agency	Project Name	Opening Balance	Additions during the year	Utilisation			Total Utilisation	Balance as on 31/03/20
					Capital Expenditure	Recurring Expenditure	Advances/ Receivables		
30	MeITY	Joint Project-Dr. Urbasi	-	2,00,00,000	-	-	-	-	2,00,00,000
31	TIFR	TIFR-Grant-Prof. Krishnakumar	55,592	-	-	4,194	-	4,194	51,398
SUB TOTAL			**9,17,97,232**	**6,72,36,849**	**2,40,29,429**	**3,70,89,271**	**(11,34,932)**	**5,99,83,768**	**9,90,50,313**
Funded by other than Government Agencies									
1	IKP	GCE Grant-Dr. Gautam Soni	(14,35,222)	20,40,798	-	9,93,491	-	9,93,491	(3,87,915)
SUB TOTAL			**(14,35,222)**	**20,40,798**	**-**	**9,93,491**	**-**	**9,93,491**	**(3,87,915)**
Retirement Funds									
1	-	Gratuity Fund	6,40,42,894	48,89,227	-	1,43,53,459	-	1,43,53,459	5,45,78,662
2		Leave Salary Fund	5,46,16,022	41,69,527	-	1,12,74,817	-	1,12,74,817	4,75,10,732
3		Pension Commutation Fund	21,89,10,430	1,67,12,838	-	1,91,06,123	-	1,91,06,123	21,65,17,145
4		RRI Pension Fund	9,43,85,285	2,27,62,614	-	65,57,419	-	65,57,419	11,05,90,480
5		RRI Provident Fund	14,86,17,234	-	-	4,10,23,835	-	4,10,23,835	10,75,93,399
SUB TOTAL			**58,05,71,865**	**4,85,34,206**	**-**	**9,23,15,653**	**-**	**9,23,15,653**	**53,67,90,418**
GRAND TOTAL			**67,09,33,875**	**11,78,11,853**	**2,40,29,429**	**13,03,98,415**	**(11,34,932)**	**15,32,92,912**	**63,54,52,816**

RAMAN RESEARCH INSTITUTE, BENGALURU
SCHEDULES FORMING PART OF BALANCE SHEET AS AT 31ST MARCH 2020

(Amount in INR)

Schedule 4- Secured Loans & Borrowings	Current Year		Previous Year	
NOT APPLICABLE	-	-	-	-
TOTAL		-		-

Schedule-5- Unsecured Loans & Borrowings	Current Year		Previous Year	
NOT APPLICABLE	-	-	-	-
TOTAL		-		-

Schedule 6- Deferred Credit Liabilities	Current Year		Previous Year	
NOT APPLICABLE	-	-	-	-
TOTAL		-		-

Schedule-7- Current Liabilities & Provisions	Current Year		Previous Year	
A. CURRENT LIABLITIES				
1. Sundry Creditors				
a) for goods	25,26,428		-	
b) Others **(Includes earnings to be transferred to BHARATKOSH)**	28,19,590	53,46,018	37,82,013	37,82,013
2. Earnest Money Deposit		6,89,500		8,43,000
3. Advances Received		1,00,00,000		1,00,00,000
4. Statutory Liabilities				
a) Overdue				
b) Others	-		-	
5. Other Current Liabilities (Incl. Security Deposit)	18,53,136	18,53,136	38,75,910	38,75,910
TOTAL (A)		**1,78,88,654**		**1,85,00,923**
B. PROVISIONS				
1. Gratuity	-		1,41,756	
2. Superannuation / Pension	-		2,70,939	
3. Accumulated Leave Encashment	-		-	
4. Others (Specify)	12,40,800		44,74,101	
TOTAL (B)		**12,40,800**		**48,86,796**
TOTAL (A+B)		**1,91,29,454**		**2,33,87,719**

RAMAN RESEARCH INSTITUTE, BENGALURU
SCHEDULES FORMING PART OF BALANCE SHEET AS AT 31ST MARCH 2020

Schedule 8- Fixed Assets											(Amount in INR)
Description		**GROSS BLOCK**				**DEPRECIATION**				**NET BLOCK**	
	Rate	Cost /Valuation as at the beginning of theyear	Additions During the year	Deductions during the year	Cost / Valuation at the end of the year	As at the beginning of the year	On additions during the year (Incl. on the OB)	On deductions during the year	Total upto the year end	As at the end of current year	As at the end of Previous Year
A. Fixed Assets											
1. Land											
a) Freehold											
Malleshwaram	-	3,78,735	-	-	3,78,735	-	-	-	-	3,78,735	3,78,735
RMV II Stage	-	31,19,436	-	-	31,19,436	-	-	-	-	31,19,436	31,19,436
HMT Jalahalli	-	8,00,63,261	-	-	8,00,63,261	-	-	-	-	8,00,63,261	8,00,63,261
2. Buildings											
a) On freehold land	1.63	19,08,26,176	29,66,855	-	19,37,93,031	3,88,86,070	31,34,933	-	4,20,21,003	15,17,72,028	15,19,40,106
3. Canteen Infrastructure	4.75	43,83,940	25,969	-	44,09,909	18,41,773	2,09,471	-	20,51,244	23,58,665	25,42,167
4. Plant Machinery, Equipment	4.75	101,14,97,839	4,13,37,216	-	105,28,35,055	47,37,75,041	4,97,42,044	-	52,35,17,085	52,93,17,970	53,77,22,798
5. Vehicles	9.50	74,51,930	-	-	74,51,930	67,78,048	6,73,881	-	74,51,929	1	6,73,882
6. Furniture & Fixtures	6.33	1,52,68,456	6,74,685	-	1,59,43,141	1,10,18,518	10,06,084	-	1,20,24,602	39,18,539	42,49,938
8. Computer Peripherals	16.21	16,59,60,825	71,92,897	-	17,31,53,722	15,65,70,624	16,18,786	-	15,81,89,410	1,49,64,312	93,90,201
9. Library Books	4.75	23,03,80,443	8,09,515	-	23,11,89,958	14,38,66,539	1,09,78,537	-	15,48,45,076	7,63,44,882	8,65,13,904
Total Fixed Assets		**170,93,31,041**	**5,30,07,137**	**-**	**176,23,38,178**	**83,27,36,613**	**6,73,63,736**	**-**	**90,01,00,349**	**86,22,37,829**	**87,65,94,428**
B. Work in Progress											
Capital Assets		4,65,41,445	2,89,74,549	3,73,32,586	3,81,83,408	-	-	-	-	3,81,83,408	4,65,41,445
Total Capital Work in Progress		**4,65,41,445**	**2,89,74,549**	**3,73,32,586**	**3,81,83,408**	**-**	**-**	**-**	**-**	**3,81,83,408**	**4,65,41,445**
Grand Total		**175,58,72,486**	**8,19,81,686**	**3,73,32,586**	**180,05,21,586**	**83,27,36,613**	**6,73,63,736**	**-**	**90,01,00,349**	**90,04,21,237**	**92,31,35,873**
Previous Year		**168,86,01,051**	**10,50,29,852**	**3,77,58,417**	**175,58,72,486**	**76,75,50,045**	**6,51,86,568**	**-**	**83,27,36,613**	**92,31,35,873**	**92,10,51,006**

RAMAN RESEARCH INSTITUTE, BENGALURU
SCHEDULES FORMING PART OF BALANCE SHEET AS AT 31ST MARCH 2020

(Amount in INR)

Schedule 9- Investments from Earmarked/Endowment Funds	Current Year	Previous Year
1. In Fixed Deposits		
RRI Pension Fund	10,26,64,250	9,51,18,276
RRI Provident Fund	8,98,12,551	13,10,59,525
Other Grants & Funds	3,74,00,000	9,62,00,000
2. Other Approved Securities	-	-
3. Shares	-	-
4. Debentures / Bonds	-	-
5. Retirement funds invested in SBI Life Insurance Limited	31,86,06,539	33,75,69,346
Claim (to be submitted) pending towards settlements made during the year	4,47,34,399	-
TOTAL	**59,32,17,739**	**65,99,47,147**

Schedule-10 Investment (Others)	Current Year	Previous Year
1. In Government Securities	-	-
2. Other Approved Securities	-	-
3. Shares	-	-
4. Debentures / Bonds	-	-
5. Subsidiaries and Joint Ventures	-	-
6. Others (Specify)-Fixed Deposits	1,00,00,000	1,00,00,000
TOTAL	**1,00,00,000**	**1,00,00,000**

RAMAN RESEARCH INSTITUTE, BENGALURU

SCHEDULES FORMING PART OF BALANCE SHEET AS AT 31ST MARCH 2020

(Amount in INR)

Schedule 11- Current Assets, Loans & Advances	Current Year		Previous Year	
A. CURRENT ASSETS				
1. Inventories		6,83,440		10,75,768
2. Cash balances in hand (Including cash imprest)		300		281
3. Unused stamp value on Postal Franking Machine		8,620		14,407
4. Bank Balances				
Main Account				
In Current Accounts	60,82,104		30,05,599	
In Savings Bank Account	-	60,82,104	9,55,302	39,60,901
Pension Fund Account				
In Current Accounts	60,46,526		11,89,092	
In Savings Bank Account	2,38,725	62,85,251	2,31,104	14,20,196
Provident Fund Account				
In Current Accounts	71,66,924		1,02,11,267	
In Savings Bank Account	10,35,266	82,02,190	8,96,527	1,11,07,794
Extra Mural Grants				
In Savings Bank Account	2,09,83,033	2,09,83,033	16,81,309	16,81,309
TOTAL (A)		**4,22,44,938**		**1,92,60,656**
B. LOANS/ADVANCES AND OTHER ASSETS				
1. Advances and other amounts recoverable in cash				
On Capital Account				
a) Land	9,25,90,600		9,25,90,600	
b) Capital Assets	1,48,98,093	10,74,88,693	1,16,53,295	10,42,43,895
Deposits		33,53,632		36,33,632
Others		1,43,78,586		1,29,43,302
2. Income Accrued				
Main Account	4,62,022		31,66,082	
Provident Fund Account	77,36,991		29,20,069	
Pension Fund Account	36,59,128	1,18,58,141	45,42,923	1,06,29,074
3. Claims Receivable				
Main Account	20,52,073		14,76,302	
Extra Mural Grants	29,53,620		27,53,620	
Provident Fund Account	21,29,048		13,42,147	
Pension Fund Account	16,71,265	88,06,006	10,47,275	66,19,344
TOTAL (B)		**14,58,85,058**		**13,80,69,247**
TOTAL (A+B)		**18,81,29,996**		**15,73,29,903**

RAMAN RESEARCH INSTITUTE, BENGALURU

SCHEDULES FORMING PART OF INCOME & EXPENDITURE ACCOUNT FOR THE YEAR ENDED 31ST MARCH 2020

(Amount in INR)

Schedule 12- Income from Sales/Service	Current Year	Previous Year
NOT APPLICABLE	-	-
Total	**-**	**-**

Schedule 13- Grants/Subsidies	Current Year	Previous Year
1. Central Government		
Grants-in-aid		
i) Non-Plan	-	-
ii) Deferred Grant (To the extent of depreciation chargeable)	6,73,63,736	6,51,86,568
iii) Recurring	46,87,96,000	44,35,95,000
Total	**53,61,59,736**	**50,87,81,568**

Schedule 14- Fees/Subscriptions	Current Year	Previous Year
NOT APPLICABLE	-	-
Total	**-**	**-**

Schedule 15- Income from Investments	Current Year	Previous Year
Interest on Investment from Earmarked / Endowment Fund	4,61,71,700	4,46,09,763
Less: Transferred to Earmarked / Endowment Fund	4,61,71,700	4,46,09,763
Total	**-**	**-**

Schedule 16- Income from Royalty/Publication	Current Year	Previous Year
NOT APPLICABLE	-	-
Total	**-**	**-**

Schedule 17- Interest Earned	Current Year	Previous Year
1) On Term Deposits		
a) With scheduled banks	-	-
2) On accounts with banks		
a) Attributable to Core grant funds **(transferable to Bharatkosh)**	17,85,815	22,82,539
b) Attributable to Own/other funds	56,34,849	58,77,206
3) On Loans/Advances		
a) Employees	1,26,229	3,02,272
Total	**75,46,893**	**84,62,017**

RAMAN RESEARCH INSTITUTE, BENGALURU

SCHEDULES FORMING PART OF INCOME & EXPENDITURE ACCOUNT FOR THE YEAR ENDED 31ST MARCH 2020

(Amount in INR)

Schedule 18- Other Income	Current Year	Previous Year
1) Profit on sale/disposal of assets		
a) Own Assets	-	-
b) Assets acquired out of grants	-	-
2) Miscellaneous Income	76,75,314	67,60,017
Total	**76,75,314**	**67,60,017**

Schedule 19- Increase/(Decrease) in stock of finished goods	Current Year	Previous Year
NOT APPLICABLE	-	-
Total	**-**	**-**

Schedule 20- Establishment Expenses	Current Year	Previous Year
a) Salaries & Wages	18,21,99,896	13,64,49,714
b) Allowances & Bonus	4,75,31,406	7,71,25,837
c) Contribution to NPS	58,93,498	34,35,021
d) Staff welfare expenditure	1,85,78,293	1,32,45,661
e) Retirement/Terminal benefits	9,30,21,792	8,75,98,200
Total	**34,72,24,885**	**31,78,54,433**

Schedule 21- Other administrative expenses	Current Year	Previous Year
1) Advertisement	8,51,068	2,30,089
2) Amenities	12,20,881	19,79,524
3) Audit Fee	70,800	64,900
4) Bank Charges	1,41,531	2,15,613
5) Campus Maintenance	1,95,47,199	1,66,22,707
6) Conveyance	5,04,049	4,34,321
7) Corporation Taxes	2,70,574	2,70,574
8) Creche	3,55,000	3,00,000
9) Electricity Charges	1,40,53,682	1,36,10,904

Continued on the next page

Schedule 21- Other administrative expenses (Continued)	Current Year	Previous Year
10) Entertainment & Hospitality	1,08,460	67,056
11) Freight	4,61,710	4,07,659
12) Honorarium & Professional Fee	83,82,086	60,26,841
13) Journal Subscription	43,66,687	22,27,289
14) Lease Rent (Gauribidanur)	5,12,200	5,23,492
15) Miscellaneous Expenses	12,29,483	14,51,469
16) Outreach	9,01,295	11,97,610
17) Patent Fee	10,79,611	4,71,500
18) Payroll Processing Charges	4,59,170	4,14,430
19) Ph.D Programme Expenditure	9,04,767	16,89,778
20) Postage & Courier Charges	1,29,610	1,31,376
21) Printing & Stationery	7,27,964	3,99,611
22) Repairs & Maintenance	1,08,16,059	79,63,096
23) Security Charges	83,57,186	89,59,296
24) Seminar/Conference	17,11,331	12,68,710
25) Stores & Consumables	4,40,87,939	4,43,42,105
26) Telephone & Communication	11,40,360	15,25,933
27) Travel Expenditure	60,00,321	90,72,250
28) Uniform & Livery	1,81,614	2,29,194
29) University Affiliation Fee	6,00,000	6,00,000
30) Vehicle Maintenance	28,24,275	24,71,382
31) Visiting Students Programme	38,11,898	39,14,740
32) Water Charges	7,67,588	7,12,920
Total	**13,65,76,398**	**12,97,96,369**

Schedule 22- Expenditure on Grants / Subsidies	Current Year	Previous Year
NOT APPLICABLE	-	-
Total	**-**	**-**

Schedule 23- Interest	Current Year	Previous Year
NOT APPLICABLE	-	-
Total	**-**	**-**

RAMAN RESEARCH INSTITUTE, BANGALORE

Schedule-24

SIGNIFICANT ACCOUNTING POLICIES

1. General

The Financial Statements have been prepared under the historical cost convention, on accrual basis of accounting and in accordance with generally accepted accounting principles. The presentation of final accounts is as per the Uniform Accounting Format for Central Autonomous Bodies as prescribed by Controller General of Accounts, Government of India

2. Fixed Assets

Fixed Assets are stated at cost of acquisition that includes inward freight, duties, taxes and incidental expense to bring the asset to use. To confirm with presentation in the Uniform Accounting Format, advance payments for procurement of capital assets have been shown in Schedule-8 (fixed assets) Capital work-in-progress. No depreciation is charged on such items. Utilisation of grants received under the component, grants for Creation of Capital Assets is shown in Schedule-1 (Capital Fund). The value of assets, as stated in Schedule-8, is nett of depreciation.

3. Depreciation

Depreciation is charged on **STRAIGHT LINE BASIS** at the following rates

a. Buildings @ 1.63 %
b. Capital Equipment, Canteen Infrastructure and Books @ 4.75%
c. Computer & Peripherals @ 16.21%
d. Vehicles @ 9.50%

Depreciation is charged in the Income & Expenditure account. Full depreciation is charged on assets added before 30th September. Depreciation on assets added after 30th September is charged at 50%. In respect of asset blocks that end with a book value less than Re 1/- on applying depreciation, the book balance is closed with a notional value of Re 1/- by limiting depreciation charged to the notional book value.

4. Inventory

Stock on hand, such as spares, stationery and consumables are valued at cost

5. Government Grants

Grants received from Department of Science & Technology, Govt. of India under **SALARIES, GENERAL** and **CREATION OF CAPITAL ASSETS** is Accounted for as Core Grants.

Grants with specific sanction for recurring expenditure is shown under Income & Expenditure Account. Unspent balance, which is nett of expenditure incurred during the year, is reported in the balance sheet under Schedule 1 (Grant Balances-Recurring Grant).

Grants received for Creation of Capital Assets received during the year is added to the previous year's balance in the Balance Sheet. Unspent balance, which is nett of utilisation during the year, is shown under Schedule-1 (Grant Balances-Non Recurring Grant). Funds utilised to Create Capital Assets is shown as an addition in the Capital Fund as per AS-12.

The Institute also receives Extra Mural Grants from various funding agencies. Such grants are shown as part of Schedule 3 (Earmarked / Endowment Funds).

6. Foreign Currency Transactions

Transactions denominated in Foreign Currency are accounted for at the rates prevailing on the date of actual transaction. No provision is made to account for gains and losses arising out of exchange fluctuations.

7.	Retirement Benefits	The Institute's contribution to Provident Fund and Pension Fund are charged to Income & Expenditure Account. Deficit, if any, in the Provident Fund and Pension Account is being provided for in the books to the extent not met out of reserves

Schedule-25

CONTINGENT LIABILITIES AND NOTES ON ACCOUNTS

A. Contingent Liabilities

1.	Claims against the Institute not acknowledged as debt	The Institute has established Letter of Credit favoring Redington, Singapore towards procurement of High Performance Cluster vide LC 0505320IM0000302. This LC would be retired in FY21
2.	Bank guarantees given by the Institute	NIL
3.	Disputed demands in respect of taxes	An amount of **Rs. 3,77,463/-** is shown as due from the Institute on TRACES portal. The Institute has reconciled the details and is in the process of filing necessary information on the portal.

B. Notes on Accounts

1.	Current Assets, Advances & Deposits	Current Assets, Advances and Deposits have a value on realisation in the ordinary course of activities. The extent of realisation is equal atleast to the aggregate amount appearing in the Balance Sheet
2.	Employees' Retirement Benefits	a. Institute's contribution to the Provident Fund account are charged to Income & Expenditure Account of the institute b. As prescribed by the Govt. of India, the Institute has subscribed to Pension funds managed by SBI Life Insurance Company Limited, in respect of quantifiable liabilities of service benefits like Gratuity and Cash equivalent of Earned Leave. The Institute has also covered its liabilities for Commuted Value of Pension c. The amounts standing to the credit of the funds in SBI Life Insurance Company Limited are held in the name of the Institute in a fiduciary capacity. Balances appearing in the fund statements as at the close of financial year is shown under Schedule-3 (Earmarked/Endowment Funds-Retirement Funds). Interest earned, if any, during the year is treated as an Addition to the fund and reported accordingly in Schedule-3. Payouts on retirement on account of Gratuity, Cash equivalent of Earned Leave and Commuted value of Pension is through the fund. d. The institution has stopped further contributions to Retirement Funds since 2011 as the existing investments representing the retirement funds are earning interest. Evaluation of the adequacy of retirement funds is taken up once in 5 years and in that cycle, the evaluation will be carried out in the ensuing financial year. In view of this, no provision has been made during the year in respect of incremental liability, if any. Benefits are paid to the retiring employees out of the institutional funds. Institution treats the pay-outs as expenses of the year if the funds are not drawn by way of reimbursement from the retirement funds. As at 31-3-2020, there is a reimbursement amount pending in respect of retirement benefits paid during the year and is disclosed separately under the Investments from Earmarked Funds.

e. In pursuance of the directions of the Council, the amount representing Institute's contribution to the CPF in respect of eligible Scientific and Technical staff members (who joined the Institute before 01/01/2004) on contractual terms are allowed to exercise an option to opt for the Institute's pension scheme, on periodic renewal of their contracts for continuous engagement in the Institute upto superannuation. In FY20, in accordance with **clause 2(i) of DoPPW OM 4/1/87-P&PU (PIS-II) dated 23-07-1996**, those Scientific and Technical personnel who joined the Institute after 01-08-1992 and are bound on CPF scheme, PF balances standing to the credit of such members is transferred to the Pension corpus. Accordingly, an amount of **Rs. 3,08,10,601/-** that is outstanding under CPF-Contribution ledger of PF Account has been transferred to Pension corpus. With this change, only GPF ledger account will continue in the PF A/c. The income generated on the corpus is used to partially fund the pension liability. Deficit, if any, is met out of regular grants-in-aid.

f. Employees who have joined the Institute after 01/01/2004, are compulsorily enrolled under the New Pension Scheme

3. Advance for purchase of land

The Institute has deposited **Rs. 8,89,61,800/-** with M/s Hindustan Machine Tools Limited, being full value of a land, in pursuance of a sale agreement entered into between the Institute and HMT Limited on **13th March 2009.** The Institute, on **16/05/2018**, has remitted **Rs. 36,28,800/-** towards additional **1014 SFT** of land. With this, the total remittance to M/s HMT Limited stands at **Rs. 9,25,90,600/-.** Government of India has formally communicated their decision to transfer land to the Institute. The conveyance deed is yet to be signed pending clearance from Government of Karnataka.

It is to be noted that a part of this land is earmarked for Indian Academy of Sciences. The Academy has made a token remittance of **Rs. 1,00,00,000/-.** This is shown as part of Schedule 7 (A)-Sundry Creditors (for others) that forms part of the Balance Sheet. A matching current asset, in form of an investment, has been created in the books as shown in Schedule 10.

4. Funds of Core grants were kept in common bank account. Hence, the interest amount to be credited to Bharatkosh in compliance of rule 230(8) of GFR 2017 amounting to **Rs. 17,85,960/-** has been apportioned on the basis of monthly outstanding unspent grant balances

5. Schedules 1 to 25 are annexed to and form an integral part of the Balance Sheet as at 31st March 2020 and the Income & Expenditure Account for the year ended on that date.

6. Previous year's figures have been regrouped/reclassified, wherever necessary, to correspond with the current year's classification/disclosure

As per our report of even date
For **M/s GRSM & Associates**
Chartered Accountants
FRN 000863S

Sd/-	Sd/-	Sd/-
(Naresh V. S) Administrative Officer (i/c)	(Ravi Subrahmanyan) Director	(Gopalkrishna Hegde) Partner **M. No. 208063**

BANGALORE / 7th July 2020

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