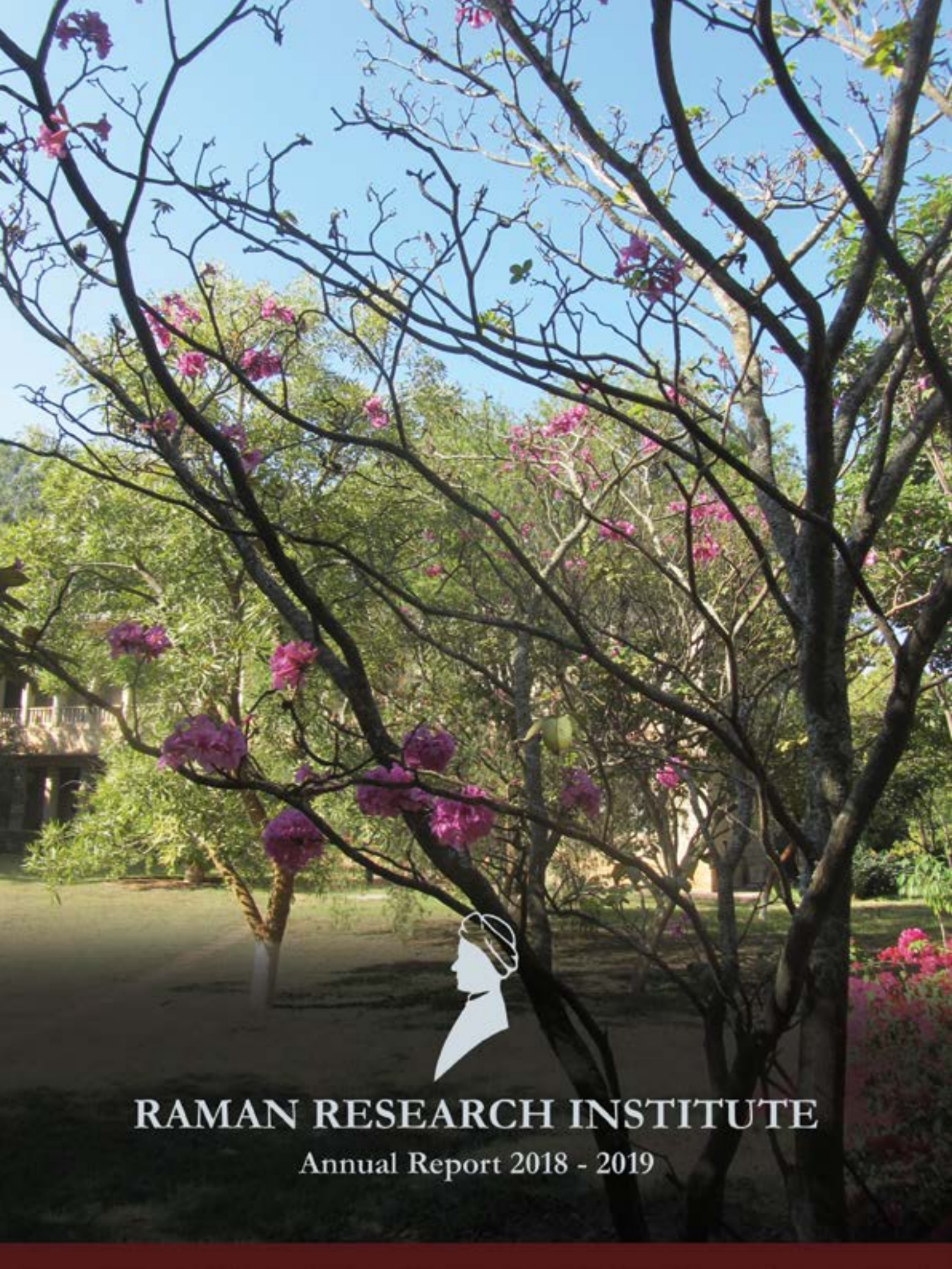
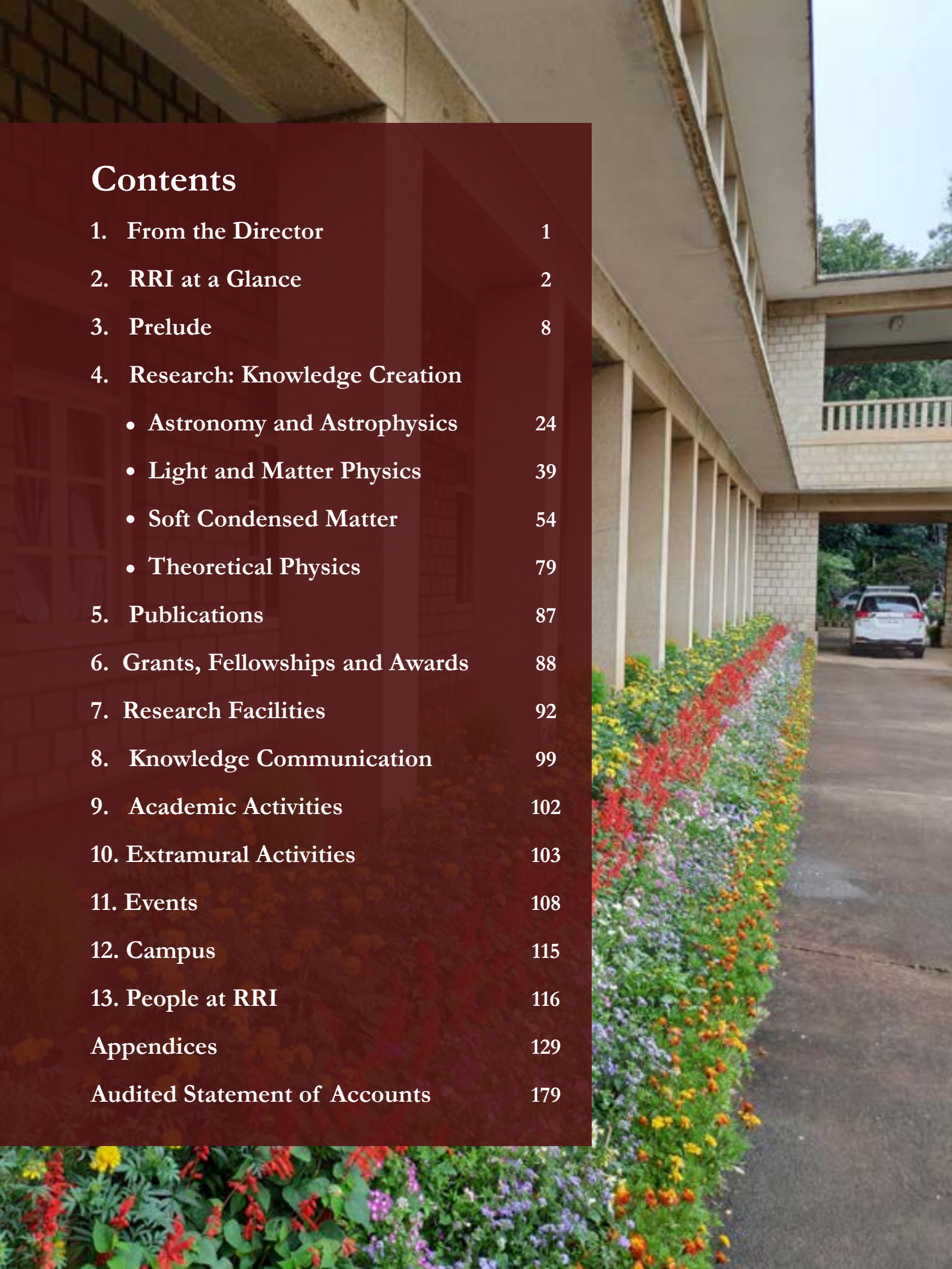


RAMAN RESEARCH INSTITUTE

Annual Report 2018 - 2019



Contents

From the Director

We owe it to the longing of the Founder – Professor C V Raman – for a place where he could pursue his passions of engaging in pure research on nature, that we have a nice campus in the city of Bangalore for the Raman Research Institute. Professor Raman grew eucalyptus trees to block the views of the outside and perhaps to insulate the Institute from the outside, took steps to insulate the research of the Institute from potential obligations and directives that might be attached to Government grants, and also built a high wall around the land.

Since 1972 RRI has been an aided autonomous research institute receiving funds from the Department of Science and Technology of the Government of India. Which naturally leads to an expectation that the research and administration of the Institute be governed by the funding agency; this happens through the representatives of the Government in the Governing Council and directives from the Department.

The Institute has responded positively to changing perceptions of the role of RRI and similar institutes that engage in research in basic sciences.

An expert committee constituted by the Department reviewed the Institute two years ago. Additionally, in 2018-19 a new procedure was introduced in which the Institute prepared a projection of the intended research, academic activities and administrative targets for the year ahead based on the funding anticipated; the document was agreed upon as a memorandum of understanding between the Institute and the Department. At the end of the year, outcomes were recorded and a performance appraisal made.

A change effected in the year 2018-19 is a reorganising of the research groups of the Institute, to engender outcomes from collective efforts of staffs with complementary technical skills. The research of the Institute has also evolved to be increasingly based on extra-mural grants and to seek to take on a few moderate-scale projects that are consistent with the strengths of the research staffs, strengths of the scientific and technical staffs, facilities, and character and size of the Institute.

As would be expected of a premier institute that derives the bulk of its funding from the Government, the choice of projects are a mix of 'dreams' that have the potential to give the Institute a visible standing amongst peers in the world of basic science research, and efforts to develop useful capabilities of more direct relevance to 'society'. Of course, given that we have staffs with higher learning, the projects undertaken and the value addition to society is based on applications of advanced concepts in science. The Institute has been through a transparent process, which involved the Governing Council, in the defining of the directions and emerging a vision that is consistent with RRI being a premier research institute of the country.

Ravi Subrahmanyan
29 August 2019

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 current 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 Lab
  - X-ray Diffraction Lab
  - SEM Lab
  - AFM Lab
  - NMR Lab
  - Micro-Raman Spectroscopy Lab
  - 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*
President, The Indian National Science Academy, New Delhi.
Honorary Professor, Department of Physics, Indian Institute of Science, Bengaluru 560012.

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

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*
President, The Indian National Science Academy, New Delhi.
Honorary 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
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Prof. Ravi Subrahmanyan
Director, Raman Research Institute (Ex-officio member) Bengaluru 560 080.

Academic Committee

Prof. Ravi Subrahmanyan, *Chairman*
Director
Raman Research Institute
Bengaluru 560 080.

Prof. Krishan Kumar
School of Environmental Sciences
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New Delhi 110 067.

Prof. R.P. Singh
School of Life Sciences
Jawaharlal Nehru University
New Delhi 110 067.

Prof. Diptiman Sen
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Indian Institute of Science
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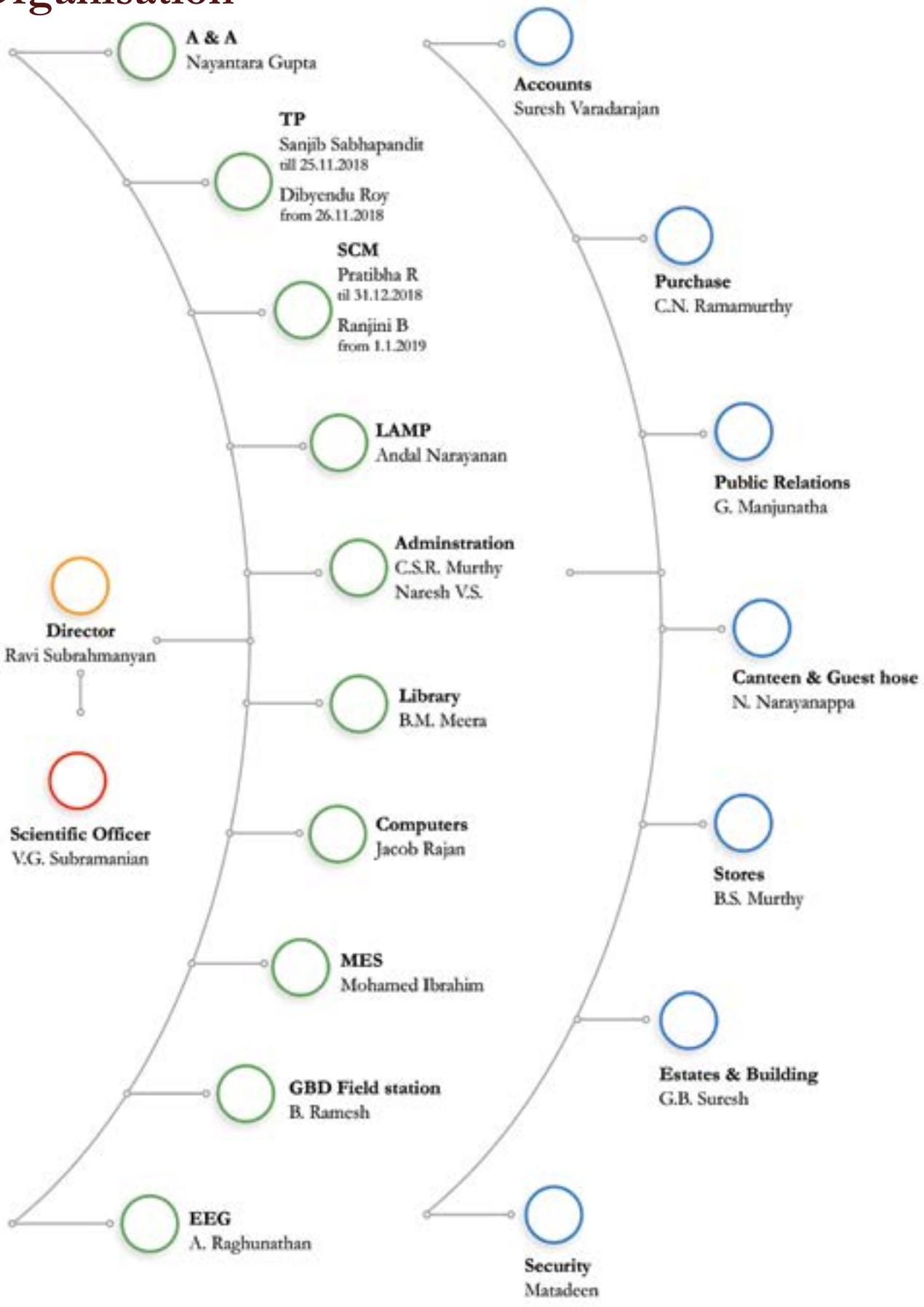
Prof. Vijay Shenoy
Department of Physics
Indian Institute of Science
Bengaluru 560 012.

Prof. V.A. Raghunathan
Soft Condensed Matter Group
Raman Research Institute
Bengaluru 560 080.

Dr. Sanjib Sabhapandit
Theoretical Physics Group
Raman Research Institute
Bengaluru 560 080.

Mr. C.S.R. Murthy, *Secretary*
Administrative Officer
Raman Research Institute
Bengaluru 560 080.

Organisation



RRI Science Forum
Gautam Soni, Andal Narayanan, Nayantara Gupta

Colloquia
Pramod Pullarkat (Chairperson), Joseph Samuel, Sadiq Rangwala, Urbasi Sinha

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

Admissions Coordinators
Saptarishi Chaudhuri, Vikram Rana

SAAC
VA Raghunathan (Chairperson), Sadiq Rangwala, Sumati Surya, Pramod Pullarkat, Shiv Sethi

In-House meeting
PhD students – 3rd year

JAP Representative of RRI
B Ramesh

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

Overseas Travel Committee
Biswajit Paul (Chairperson), Reji Philip, Pratibha R

Evaluation Committee
KS Dwarakanath (Chairperson), Sumati Surya, Biman Nath, VA Raghunathan, Sadiq Rangwala

Coordinator of Visiting Students Programme
CSR Murthy

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

RRI Official Language Implementation Committee
CSR Murthy (Chairperson), VS Naresh, Suresh Varadarajan, R Ramesh, CN Ramamurthy, B Srinivasamurthy, BM Meera, G Manjunatha, K Radhakrishna, V Vidyamani, Harini Kumari, Mamatha Bai, 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 Post-doctoral, 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 Post-doctoral 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 2018-19

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. For example, gamma-ray emission in the shape of bubbles is detected outwards from the center of our Milky Way galaxy by the Fermi LAT detector; these are known as Fermi bubbles. 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 2018-19 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.

Galactic Outflows

Detailed simulations by Biman Nath and collaborators Eugene Vasiliev and Yuri Shchekinov, in which they varied Star Formation Rate, gas density and gas scale height, led to the deduction of a threshold energy injection rate density required to launch gaseous outflows from star forming galaxies; this compares well with observations. Comparison of multi-wavelength simulations of the observational effects of cosmic rays emanating from superbubbles with actual observations, by Siddartha Gupta, Biman Nath and collaborator Prateek Sharma, has led to the identification of wind termination shock as the site of cosmic ray acceleration. Current research efforts by Aditi Vijayan and Biman Nath are towards inferring the physics behind synchrotron radio halos by comparing simulated radio maps with observations of edge-on star-forming galaxies.

Resonant transport of angular momentum in galaxies

Karamveer Kaur and S Sridhar have solved the long-standing problem of why the orbits of globular clusters (GCs) appear to 'stall' in the cores of dwarf galaxies, in contradiction with the predictions of Chandrasekhar's dynamical friction formula. They found that due to the progressive loss of strong resonances at small radii, the net torque was suppressed by factors of 100 to 10,000 compared to the Chandrasekhar torque; this results in the appearance of stalling at an orbital radius between 200 and 300 parsecs.

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.

Saikat Das, Nayantara Gupta and their collaborator Soebur Razzaque have studied the composition, source distribution and propagation of ultra-high-energy cosmic rays. This study reveals the problems in explaining the origin of ultra-high-energy cosmic rays if the highest energy cosmic rays are heavy nuclei. During the past year, Nayantara Gupta and collaborator Samaresh Mondal have suggested synchrotron cooling of two populations of accelerated electrons in each knot of the extended jets of six quasars to explain the radio to optical and the X-ray emission from these quasars. Modelling of the flaring and quiescent state of a variable Blazar using multi-wavelength data from various observatories across the world, by Raj Prince, Nayantara Gupta and collaborator Krzysztof Nalewajko, has led to the inference that there could be multiple emission zones for the different wavelength bands along the jet axis of the Blazar. Sayan Biswas and Nayantara Gupta have calculated the gamma-ray background from interactions of Galactic cosmic ray protons with the interstellar matter. Upon comparing with the observed IGRB (Isotropic Gamma Ray Background) above Galactic latitude $|b| > 20$ degree, they concluded that IGRB is mostly of extragalactic origin as the Galactic contribution is small.

Cosmology

Using a formulation suitable for statistical detection of the redshifted 21-cm signal, Jankee Rastee and Shiv Sethi have shown that the early phase of the Epoch of Reionization, which is dominated by heating, Lyman-alpha and/or density inhomogeneity, can be studied using topological properties of the heated/Lyman-alpha coupled regions. Their results are in reasonable agreement with existing numerical results. In another work, Shiv Sethi and collaborators Kanhaiya Pandey and Bharat Ratra have proposed a mechanism that could explain the presence of supermassive black holes. They identify "magnetic braking", a process in which the primordial magnetic field removes the angular momentum during spherical collapse and thereby leads to a lowering of the angular momentum barrier, as a possible reason that allows the formation of supermassive black holes. Studies of the cosmological implications of the formation of the first stellar-size black holes, by Shiv Sethi and collaborators, have provided magnitude estimates for the 21-cm signal. They have further shown that current and upcoming

radio interferometers might be able to detect the neutral hydrogen H I 21 cm line, the hyperfine line of 3He II, and the H II recombination lines in the region around a growing black hole.

The EDGES collaboration had claimed detection of 21-cm signal that was at least a factor of two larger than standard theoretical predictions and had features that required evoking exotic physics to explain them. Using realistic model for foregrounds, Saurabh Singh and Ravi Subrahmanyan have shown that the data could be equally well explained by presence of an unmodeled, plausible systematic that had escaped their calibrations. In such a case, the data was shown to be consistent with a class of 21-cm signals predicted assuming standard cosmology, without any exotic physics.

Avinash Deshpande has proposed a critical dipole test based on a unique correspondence between the intrinsic monopole spectrum and the differential spectrum as an imprint of dipole anisotropy (DA) resulting from the motion of observer with respect to the rest frame of the source, that the measurements of the monopole component of the spectrum of interest should necessarily pass. Such a dipole qualifier for the monopole spectrum, when combined with reliable foreground estimation, is expected to pave way for in situ validation of spectral signatures from early epochs, which are important to presently reported and future detections of Epoch of Reionization (EoR) signal.

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.

Radio Astronomy

A broad-band study of the radio relic in the galaxy cluster Abell 4038 using the Upgraded Giant Metrewave Radio Telescope (uGMRT) conducted by Viral Parekh, K S Dwarakanath and collaborator Ruta Kale has enabled them to interpret the morphology and spectral properties of the relic in the scenario of an adiabatically compressed cocoon from the past activity of the brightest cluster galaxy in the cluster.

During the past year, efforts by Avinash Deshpande and collaborators were towards studying the variability in the properties of local pulsars and that of the intervening medium. Targeted observations to search for pulsars and fast transients are continuing at 34.5 MHz, using the Gauribidanur Radio Telescope. Efforts were also towards studying the distribution of pulsars, and assessment of underlying processes that govern their distribution. The phenomenon of subpulse drifting offers unique insights into the emission geometry of pulsars, and is commonly interpreted in terms of a rotating carousel of spark events near the stellar surface. Avinash Deshpande and collaborators have developed a detailed geometric model for the emission columns above a carousel of sparks that is entirely calculated in the observer's inertial frame, and which is consistent with the well-understood rotational effects of aberration and retardation. In another work, detailed analysis of the drift pattern obtained through improved pulsar data analysis by Avinash Deshpande and collaborator Hrishikesh Shetgaonkar has suggested a system of 19 sub-beams rotating around the magnetic axis of pulsar B0809+74. During the past year Jigisha Patel and Avinash Deshpande have revisited the phenomenon of lunar occultation, which occurs when the Moon crosses sight-lines to distant sources. In a paper published during the past year, they describe details of this investigation, relevant to radio frequencies at which Fast Radio Bursts have been detected, and discuss their findings, along with implications.

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, system dynamics like orbital period and radius evolution of X-ray binaries, structural evolution of the accretion disk and its time scales, and structures of the stellar wind can be obtained by a careful analysis of the X-ray output from compact X-ray binaries. A brief overview of various aspects of compact X-ray sources investigated by RRI astronomers during 2018-19 is given below.

Studies of the high-resolution X-ray spectrum of an

accreting X-ray pulsar by Gayathri Raman, Biswajit Paul and collaborator Pragati Pradhan has led to the detection of a multitude of iron lines including a Compton scattered component which reveals the presence of dense matter surrounding the X-ray source as well as Hydrogen-like and Helium-like lines indicative of a highly ionized surrounding medium. Studies undertaken by Biswajit Paul and collaborators of a transient X-ray binary pulsar in the Small Magellanic Cloud during its outburst in late 2017 has led to the detection of a Cyclotron Resonance Scattering Feature at ~5 keV in the X-ray spectrum, independent of the choice of the continuum model, which indicates a magnetic field strength of 6×10^{11} G for the neutron star. The study of X-ray reprocessing - a key diagnostic tool to probe the environment in X-ray binary systems - was undertaken for nine high mass X-ray binaries (HMXBs) by Nafisa Aftab, Biswajit Paul and collaborator Peter Kretschmar. The studies have revealed significant differences in the eclipse spectrum of different HMXBs and also in their eclipse spectra against out-of-eclipse spectra. Biswajit Paul, Biman Nath and collaborators have constructed separately the composite spectra of galactic High Mass X-ray Binaries (HMXBs) and Low Mass X-ray Binaries (LMXBs) and used it to study the impact of these sources on the 21-cm signal using the outputs of N-body simulation and 1D radiative transfer. The heating due to the composite spectrum was found to be less patchy compared to power-law spectrum with a spectral index $\alpha = 1.5$, used in previous studies while the amplitude of the heating peak of large scale power spectrum, when plotted as a function of the redshift, was found to be less for the composite spectrum. During the past year, Varun, Biswajit Paul and collaborators have extensively used the LAXPC onboard ASTROSAT to study cyclotron line characteristics, pulse phase variation and thermonuclear X-ray bursts in high mass X-ray binaries.

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. Additionally, new methods and modelling aimed towards extracting the signal of interest from the background is desired. 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.

The Institute is developing and building an X-ray polarimeter (POLIX), in collaboration with ISRO, to be a payload onboard the XPoSat mission of ISRO, a first of its kind mission in the world. The POLIX instrument was conceived by RRI to measure X-ray polarization of cosmic sources. The Preliminary Design Review (PDR) of the XPoSat Satellite including the POLIX payload was conducted successfully in ISRO in September 2018. During 2018-19, significant progress has been made in making the Qualification Model of POLIX and fabrication of some of the Flight Model components of POLIX has been initiated. The MOU between RRI and ISRO for POLIX onboard XPoSat was revised and second phase of funding for POLIX was released to initiate the Flight Model of POLIX. In the area of hard X-ray optics development, a dedicated brand-new clean-room facility of 10,000 class has been constructed which is being employed for the fabrication of X-ray concentrators/optics.

In an attempt to observe the radio sky in the relatively unexplored window of very low frequencies (5-20 MHz), design and development of a very low radio frequency antenna has been undertaken during the past year by Avinash Deshpande and Pavan Uttarkar. During the year, the SWAN – Indian Sky Watch Array Network – project continued developments with RRI members Vinutha Chandrashekar, K B Raghavendra Rao, H A Aswathappa, P S Sasikumar, T S Mamatha, H N Nagaraja, Sandhya and Avinash Deshpande working with numerous students from universities across the country towards exploring the transient sky with specialized receivers and algorithms.

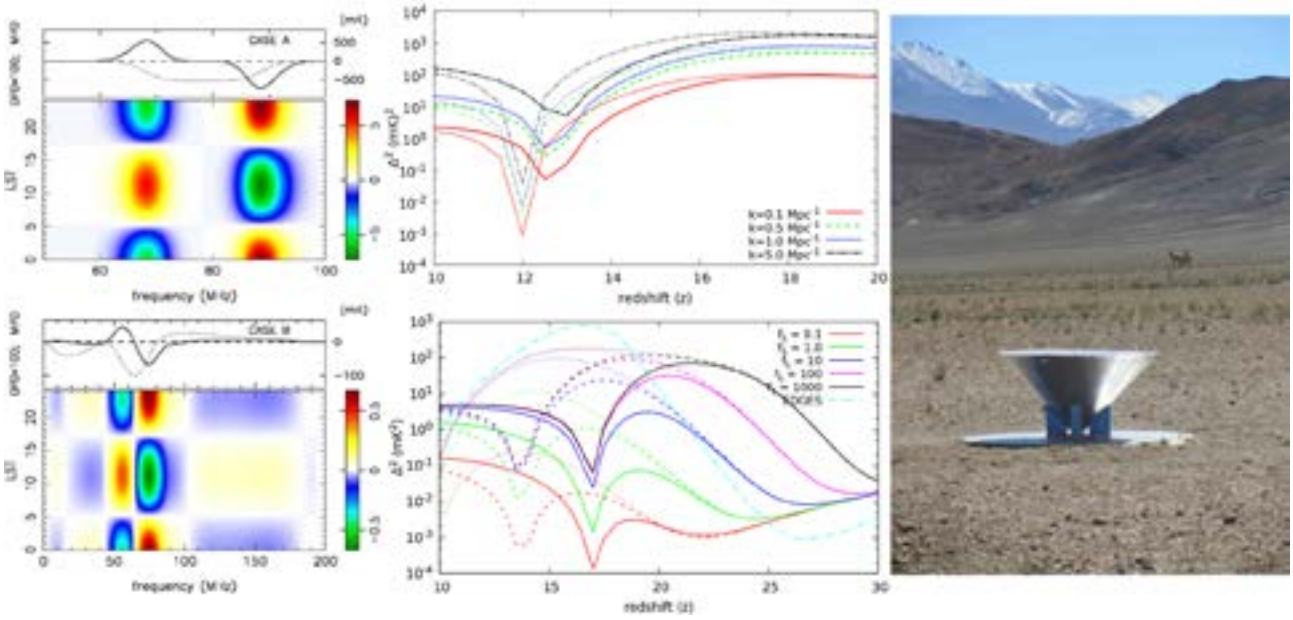
Efforts by Ramesh Balasubrahmanyam, Sandeep H, Avinash Kotla, Sandeep K, Mohit Sinha, Kamesh, Kuldeep Singh and Charles Paul has continued towards building a cm-wave imaging telescope which, by use of a novel optics scheme "efficient linear array imaging", provides good resolution, sensitivity and collection time with 70% less reflector area and easy cum cost effective manufacturing. Another telescope to search for supernova events in our galaxy, based on the One Element Interferometer scheme proposed by Ramesh Balasubramanyam, is being constructed by him and Lekshmi Nair at the RRI field station in Gauribidanur.

During the past year the SARAS 3 system - a system to detect the global 21cm signal - was field tested in relatively radio quiet regions of Timbaktu collective in Andhra Pradesh and at the Indian Astronomical Observatory at Hanle in Ladakh, which is operated by the Indian Institute of Astrophysics. Subsequent analysis of data collected by Jishnu Nambissan, Ravi Subrahmanyan, Udaya Shankar N, Saurabh Singh, Mayuri S. Rao, B. S. Girish, A Raghunathan, Somashekar R. and Srivani K. S. has shown

that the electromagnetic coupling of the antenna to ground introduces confusing structures into the measured spectra and current efforts are towards mitigating this coupling.

Algorithms & Signal Processing

Research effort 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. Research in signal processing during the past year has been towards mitigating radio frequency interference and data analysis techniques that subtract the foregrounds from mean spectrum to extract the global 21cm signal.



Left panel: The plots are results of work undertaken at RRI which proposes a critical dipole test to reliably verify that the apparent Epoch of Reionization signal is indeed from the early epochs. To know more about this work, the reader is directed to The Astrophysical Journal Letters, Volume 866, Number 1. **Middle panel:** Results from the Institute's efforts to analytically model the early phase of reionization using a formulation suitable for statistical detection of the H I signal. **Right Panel:** Precision Radiometer SARAS 3 deployed at IAO, Hanle, a site operated by the Indian Institute of Astrophysics.

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.

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 at low temperatures.

A recently started activity 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. Towards this, Saptarishi Chaudhuri along with team members Sagar Sutradhar, Subhajit Bhar, Maheswar Swar 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. A laser system whose components

were purchased from Toptica Photonics GmBH has been installed and saturation absorption spectrum of potassium and sodium atoms has been obtained. In addition to spatially transporting their cold atoms within the vacuum chamber using a magnetic relay system they performed a comprehensive computer simulation for designing the magnetic field producing coils and temporal variation of the currents in the overlapping coils. All the magnetic field producing coils required for the experiment were designed and made in-house at RRI. An IGBT based high-current fast-switching circuit was also developed. The team of Saptarishi Chaudhuri also studied spin correlation spectroscopy of cold atoms trapped in magnetic sub-levels connected by a pair of Raman transition beams. They find an enhancement of spin-correlation signal when the Raman transition detuning comes into resonance with the Larmor frequency of the magnetically trapped atoms. The effort continues to use this effect to detect small magnetization fluctuation signals from ultra-cold and quantum degenerate atomic systems.

Interactions between few-atoms and few photons have been one of the focus activities of cold atom research at RRI. Hema Ramachandran, along with Shilpa B.S. and Sanjukta Roy, have optimized the cooling and trapping mechanism required to trap atoms. Specifically, the effect of different refractive indices of the coupling and probe frequencies on the trapped atoms was identified. In addition, several atom loss mechanisms from the trap were identified and corrections incorporated leading to a lifetime of about a second.

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 types interact with each other? At ultracold temperatures, small changes in energy can make a big difference in the nature of interactions.

In earlier work it was proposed that the trapped ions and atoms have a symmetry-based quantum cooling mechanism due to 'resonant charge exchange' (RCE), which was called "swap cooling". While this was proposed and there were telling experimental signatures that the mechanism was active, it was impossible to experimentally demonstrate this in a single-species experiment. In order to prove this, cold atoms of Cs (Caesium) along with Rb (Rubidium) were co-trapped and the energy exchanged per collision was determined to be orders of magnitude higher than that in elastic collision. This result firmly establishes a new and completely quantum cooling mechanism, which has been proposed, theoretically developed and experimentally demonstrated at RRI.

Quantum optics has developed rapidly in recent times and the coupling of atoms to a cavity is at its heart. Motivated by the non-destructive interaction of trapped species, in particular, trapped molecules techniques were developed for non-destructive detection of ground state molecules. This was done as an example for Rb_2. The question of losses, which plagues molecule detection, was addressed and solved.

When a cold dilute gas of atoms couples to a cavity, they need not only couple to the fundamental transverse mode. The question of how to exploit higher order modes to detect atoms (and later molecules as above) in cavities was investigated in an elaborate experiment where the atoms are fluorescing or in dark states. Such an extension over the fundamental mode not only gives us number information but also atom density and its spatial variations, which is an extremely important quantity to measure in dilute gas experiments.

A new experiment on Li-Ca is under construction and a number of theoretical and experimental studies to better understand the system are under way. There has been an intense effort on instrumentation, which is believed to be in its final stages.

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 spectroscopy measurements from thermal vapours was carried out by Saptarishi Choudhury along with Maheswar Swar, Dibyendu Roy, Subhajit Bhar, Priyanka G L, Hema Ramachandran and Sanjukta Roy. The highlight of this research work has been the demonstration of high precision magnetometry using spin noise measurements and non-perturbative detection of atomic population in different hyperfine states.

For the past few years Asha K., Adwaith K. V., Pradosh K. N., Meena M. S. and Andal Narayanan along with collaborator Fabien Bretenaker have been experimentally studying an atom-light interaction scheme which involves light fields and atomic energy states interacting with each other in a cyclic and closed fashion. During the past year they have completed this study where they demonstrate 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.

Light transport in random media

During the past year Hema Ramachandran along with Bapan Debnath and Shankar Dhar used their previously developed quadrature lock-in detection technique to obtain on-the-field image of an object which was hidden in a strongly scattering and opaque medium. Specifically, they imaged an object 150 m away from their camera in a dense fog where the visibility was merely 50 m.

Brain-Computer Interfaces

A Brain-Computer Interface (BCI) is a fascinating and powerful system that monitors the brain signals of a subject and enables the driving of devices and performing of actions, without any actual physical movement by the subject. A BCI-speller is a device that enables paralysed persons to spell out words on a computer screen by means of certain EEG potentials that are evoked by the subject and monitored by the device. During 2018-19, a SSVEP-based speller that uses Steady-State Visually evoked potentials has been made, tested and optimized by Anubodh Yadav, Shruthi K.R., S. Sujatha and Hema Ramachandran.

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 Reji Philip and colleagues (Nithin Joy and Agnes George) tested diverse materials for their optical limiting characteristics, including discotic liquid crystals (with SCM members A. Gowda and S. Kumar) and nanostructured perovskites (with V. S. Muthukumar, SSSIHL and K. B. R. Varma, IISc).

Irradiation of a solid surface by intense laser pulses results in the generation of a plasma (Laser-produced plasma, LPP). In the past year, Reji Philip and colleagues (Pranitha Sankar, Nancy Verma) carried out a number of studies in LPPs including time-resolved optical emission spectroscopy of a picosecond laser produced Cr plasma (with K.H. Rao and R.T. Sang, Griffith University) and the effect of laser beam size on the dynamics of a femtosecond laser-produced aluminium plasma. The role of ambient gas pressure on nanosecond LPP from Ni thin films in a forward ablation geometry was studied (with J. Thomas, IPR, Ahmedabad). In addition, ultrashort pulses from a Ti:sapphire laser were used to fabricate large area nanoscale order laser-induced periodic surface structures (LIPSSs) on a silicon (100) surface [with K.K. Anoop (CUSAT, Cochin)]. Sample characterization led to the observation that the LIPSS patterns are strongly dependent on the laser pulse energy, state of polarization, number of shots delivered on the target and ambient pressure.

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.

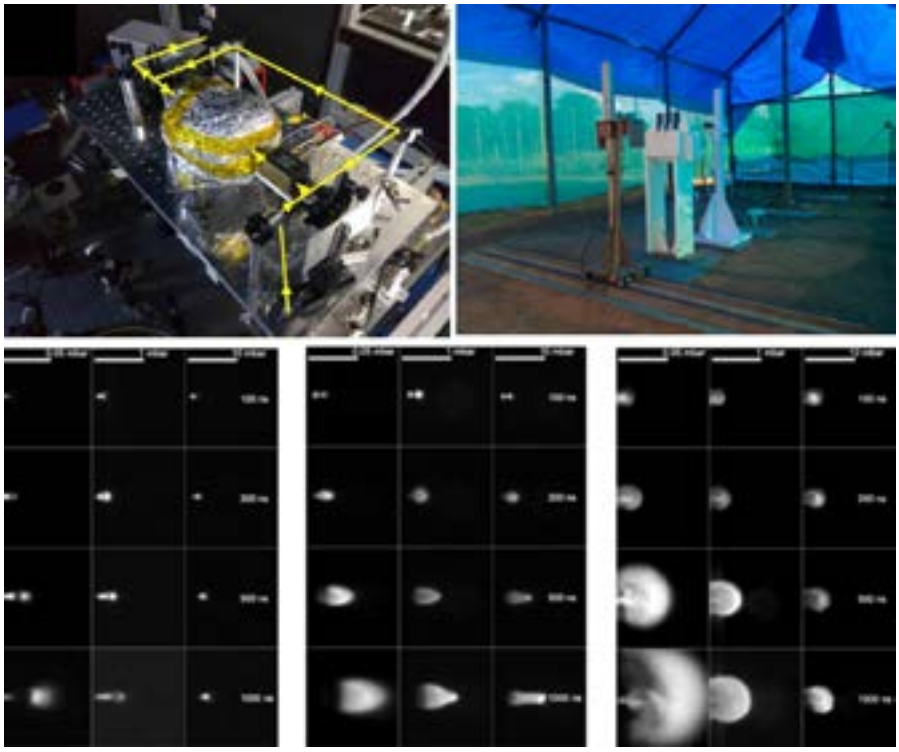
In the Quantum Information and Computing lab at RRI, Urbasi Sinha along with team members Kaushik Joarder, Rishab Chatterjee, Sourav Chatterjee, A. Nagalakshmi, A. Anuradha and Rakshita R. M. have embarked on an ambitious multi-year project to demonstrate free space quantum key distribution over different distance domains in varying environmental conditions, culminating with using a satellite as a trusted node towards long distance quantum communication. This project is in collaboration with the Indian Space Research Organization (ISRO). During the past year Urbasi Sinha and team have been able to establish a communication protocol called the B92

protocol in their lab with an average key rate of 50Kbits/ second and an average QBER of~3.5% over a~2 metre free space distance.

In a quantum optics experiment Urbasi Sinha and her group members S.Sadana, D. Ghosh, K. Joarder, A. Nagalakshmi along with collaborator B.C.Sanders (University of Calgary, Canada) show that even classical sources can show a 100% dip in intensity-intensity cross correlation measurements with proper phase control between the input pulses. They show this theoretically as well as experimentally with a carefully designed microwave experiment. This work corrects the prevalent misconception that only quantum sources of indistinguishable photons can exhibit a visibility of 100% in the Hong-Ou-Mandel dip and shows that a 100% visibility can be attained even with classical pulses. They then go on to describing the true quantum source diagnostic to be a complementarity based experiment which is performed both classically as well as with down conversion based photons. While quantum sources fulfil the Complementarity principle, classical microwaves fail to do so.

In the realm of fundamental tests of quantum theory, over the last several years Urbasi Sinha along with collaborators have been performing precision theoretical as well as experimental tests to correct the naïve application of the superposition principle in interference experiments. This year, Urbasi Sinha along with team members G. Rengaraj, U. Prathwiraj, S. N. Sahoo and R. Somashekhar performed the first experimental measure of the correction term arising due to the presence of non-classical paths in a triple-slit experiment with microwaves. This was a tunable experiment in which the strength of the correction term could be tuned which made it the first unambiguous measure of this correction term, also known as the Sorkin parameter.

Quantum theory allows direct measurement of the average of a non-Hermitian operator using the weak value of the positive semidefinite part of the non-Hermitian operator. During 2018-19, Urbasi Sinha along with G. Nirala, S. N. Sahoo and collaborator A. K. Pati (HRI, Allahabad) have experimentally demonstrated the measurement of weak-value and average of non-Hermitian operators by a novel interferometric technique. This is an example of a realm of work, both theoretical and experimental, that the team has been investigating over the past few years in the area of weak values and weak measurements.



Top left: Sodium saturation absorption spectroscopy setup located in the Quantum Mixtures laboratory. **Top Right:** The actual experimental set-up at the Gauribidanur observatory for measuring the deviation from the superposition principle in interference experiments [New Journal of Physics, Volume 20, June 2018]. **Bottom:** Temporal evolution of a rear ablated nickel plasma plume generated in a 50 nm thick Ni thin film using three different laser wavelengths and pulse widths [from Thomas et.al., J.Phys.D.Appl.Phys. 52, 135201 (2019)].

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 2018-19

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. 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 2018-19 was on the design and synthesis of novel LC's geared towards optoelectronic applications including organic light emitting diodes and other organic electronics. For example, Sandeep Kumar and collaborator A. V. Adhikari and others have designed and synthesized a new series of flying bird-shaped liquid crystalline (LC) cyanopyridone derivatives with a D–A–D architecture, CPO-1 to CPO-4. The application potential of these as an emissive material was demonstrated for the fabrication of doped and non-doped OLED devices with different device architectures. In another work, Sandeep Kumar and collaborator A. Nayak and others have developed a novel discotic dimer-DNA complex hybrid systems at air-water and air-solid interfaces which when coupled with compatible architectures could serve as a model system for organic electronics. Polymeric LCs exhibit interesting properties, which can have practical applications ranging from photonics to non-linear optics. During the past year, H. T. Srinivasa, N. Prutha and R. Pratibha have used a novel type of molecular architecture to obtain bent-core monomers by introducing naphthalene moiety in the side arms and linking them with terminal double bonds as polymerizable functional groups. Such monomers offer the possibility of stabilizing switchable LC phases and have the potential to form polar polymers useful for NLO applications. They also observed a striking temperature dependent variation in transmitted colour in the nematic phase, arising from changes in the effective birefringence, which could be utilized in LC based optical sensors. In another work, Deepshika Malkar, Arun Roy along with collaborator Veena Prasad have discovered a new type of smectic liquid crystal phases exhibited by bent core hockey stick shaped molecules which also displays birefringence induced color changes as a function of voltage, with obvious potential for applications in LC based optical sensors. Research efforts during the past year by N. Prutha and R. Pratibha has been on developing a new strategy for obtaining stable long range blue phases

(BPs) by combining chiral rod-like (R) and achiral bent-core (BC) molecules for potential applications as tunable photonic band gap materials. This study also aids in understanding the origin of enhanced BP range in such systems. Based on several experimental studies, they have shown that the BP stability may be attributed to chiral interactions between the R molecules which form double twist cylinders, and the BC molecules which lie in islands interspersed between the R molecules. The spontaneous expulsion of electro-responsive fibres composed of BC molecules, which actually reveal the presence of these islands, is another special feature. Recent research efforts at RRI have also focused on exploring the combined functionalities of LCs and nanoparticles to develop hybrid platforms with unique structure-property relationships suited for applications in optoelectronics, optical and molecular switching, energy storage and sensing devices. For example, studies by Sandeep Kumar and collaborators has shown that the insertion of QDs in chiral smectic C matrix caused localized smectic layer distortion in such a way that spontaneous polarization remains almost the same but the electro-optic switching of molecules becomes faster making them ideal candidates for energy storage applications. Sandeep Kumar along with collaborator Md. Lutfor Rahman and others has synthesized liquid crystals decorated gold nanoparticles in a molecular architecture consisting of the azobenzenes moieties with alkene as the peripheral units, connected to gold nanoparticles (Au-NPs) via thiolated phenolic units in the middle. Detailed experimental analysis has demonstrated the suitability of the Au-NPs compound in the field of optical storage and molecular switching. Theoretical research in liquid crystals by Yashodhan Hatwalne, C. Saichand and collaborators was on studying the stability of wall defects on spherical, ordered fluid membranes, developing the full phase diagram of the different possible structures in parameter space for lyotropic smectic-A liquid crystals under compression and on constructing a unified phenomenological theory that accounts for the stability of different morphologies of polymer crystallites.

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.

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.

Biophysics

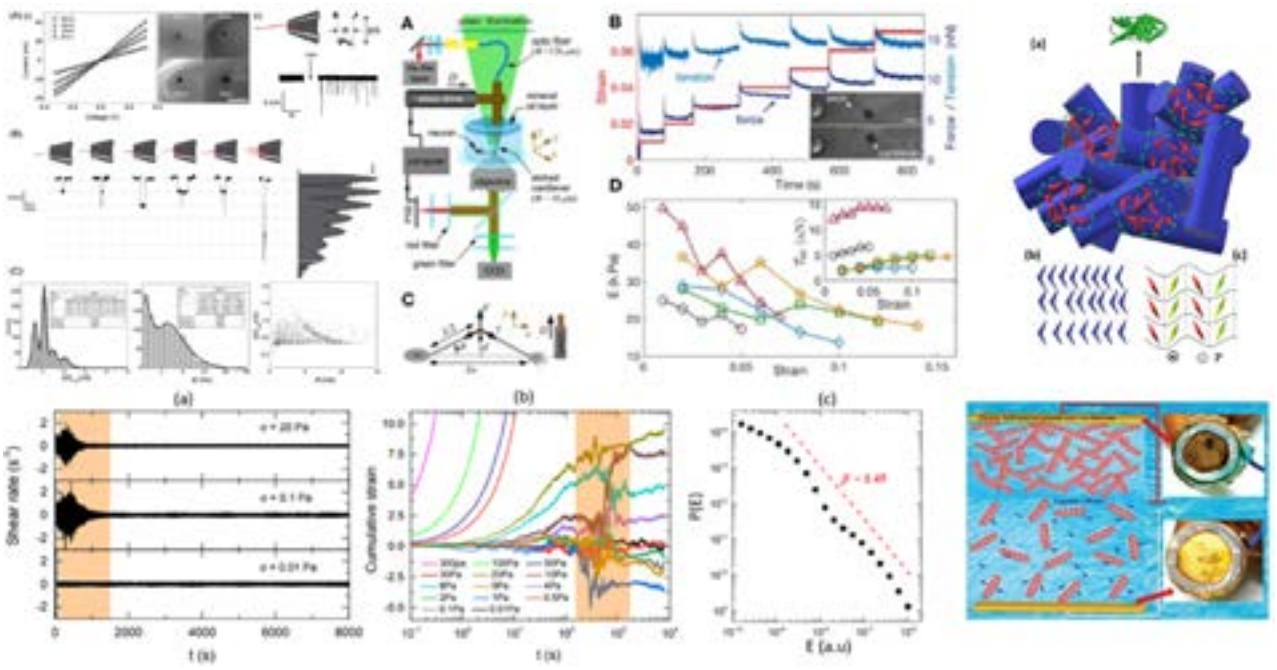
Nanoscale biophysics of biological systems

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 2018-19, two distinct single molecule methodologies to look into single DNA mechanics were developed: (1) a home-built optical tweezers system capable of manipulating single DNA molecules which will be used for measuring the structural interactions that underlie chromatin function in biological systems (2) a home-built nanopore system for screening single DNA molecules.

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 limbs) 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 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. Research in the lab had also shown that abnormal cylindrical to peristaltic shape transformations, often observed as a result of neurodegeneration, can be understood based on a mechanical model invoking plasma membrane tension and elastic responses of the internal polymer skeleton. During the past year, theoretical models have been developed,



(Top Left) Some images and results from the in-house developed Nanopore Platform for Screening (NPS) of biomolecules. A (i) shows typical images as well as I-V curves for glass (quartz) nanopores of different diameters. (ii) shows open pore conductance before and after adding DNA to the nanopore cis chamber. After adding DNA, single DNA molecules are detected translocating through the nanopore in the form of electrical blockade events. B shows a variety of DNA polymer configurations as it translocates through the pore. All polymer configurations are uniquely identified in the nanopore system. The histogram on the right shows translocation events corresponding to 1,2,3... and so on number of DNA molecules detected using the nanopore. C shows the typical conductance blockades (dG) & dwell time (dt) histograms of about 1000 DNA molecules passing through the nanopore. The dG-dt scatter plot is shown to visually contrast configurational population of DNA molecules translocating through 20 nm glass nanopores. **(Top Middle)** (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. **(Top Right)** Schematic representation of clusters of B7 fibres revealing origin of Blue phase stability in a binary mixture of chiral rod-like and achiral bent-core (BC) molecules (a) islands composed of randomly oriented BC molecules interspersed between chiral R molecules forming DTCs. (b) Lamellar arrangement formed by the BC molecules within the islands. (c) Layer undulations in the B7 phase. **(Bottom Left)** (a) Earthquake seismograph like burst events in shear rate fluctuations as a function of time for different applied Stress values below yield stress (~27 Pa). (b) Cumulative strain obtained from the time integration of the data in (a) for different stress values both below and above the yield stress. Below yielding, in the time window corresponding to shear rate Burst, sudden reorganizations happen in the system. (C) Distribution of kinetic energy of the shearing plate shows power-law behaviour, consistent with Gutenberg-Richter law for real earthquakes. **(Bottom Right)** A graphical representation of studies on LAPONITE clay suspensions upon application of a DC electric field. This work is published in Soft Matter, 2018,14, 6974-6982.

which supports a membrane tension driven mechanism where the nature of microtubule depolymerisation dictates whether the axonal atrophy occurs via beading or retraction. 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.

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 and Statistical 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 foundational questions in quantum mechanics, quantum information and precision measurements using atomic systems. The overlap with the Soft Condensed Matter group is in areas such as biophysics, polymer physics and modelling stochastic search process.

Focus 2018-19

Statistical Physics

Statistical physics gives a probabilistic description of systems that evolve in a stochastic manner. Examples of such systems include the motion of colloidal particles in water, motion of bacteria, externally shaken granular particles, as well as gas in equilibrium. For equilibrium systems, there is a well-defined formalism to study the static properties. However, for systems away from equilibrium, there is no standard method. During the past year, Sanjib Sabhapandit and his students at RRI along with collaborators investigated such nonequilibrium systems using various mathematical methods: (a) Sanjib Sabhapandit and collaborators Abhishek Dhar, Anupam Kundu, Satya N. Majumdar, and Gregory Schehr studied the steady state, relaxation and first passage properties of a one-dimensional run and tumble particle subjected to confining potentials. (b) Sanjib Sabhapandit and Santanu Das along with collaborator Deepak Dhar studied the statistics of overtake events by a tagged agent by considering a minimalist model of overtaking dynamics in one dimension. (c) Studies on the velocity distribution of a driven granular gas by Sanjib Sabhapandit and collaborators has revealed contradictions to the predictions of the phenomenological kinetic theory, necessitating a re-examination of its basic assumptions.

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. Studies on active Brownian motion in two dimensions by Urna Basu and collaborators Satya N. Majumdar, Alberto Rosso and Gregory Schehr has revealed that at short times the presence of activeness results in a strongly anisotropic and nondiffusive dynamics in the (xy) plane and at early times, the active Brownian particles has anomalous first-passage properties, characterized by non-Brownian exponents. Stochastic resetting, which refers to intermittent interruption and restart of a dynamical process, has been a subject of immense interest in recent years. Studies during the past year by Urna Basu along with collaborators Anupam Kundu and Arnab Pal of the behaviour of a Symmetric Exclusion Process (SEP) in presence of stochastic resetting where the configuration of the system is reset to a step-like profile with a fixed rate r showed that the presence

of resetting affects both the stationary and dynamical properties of SEP strongly.

Josephson junctions are an essential building block of modern quantum electronics and precision measurements. Such junctions with exotic topological superconductors (TS) hosting Majorana quasiparticles have been predicted to be an integral component of future quantum devices; e.g., fault-tolerant quantum computers. While there are many theoretical studies over the last two decades for steady-state transport in hybrid junctions of TS wires, a very fundamental question remains unexplored: is there a unique nonequilibrium steady-state in such hybrid devices of TS and normal metal wires? A negative answer to this question would pose a severe challenge to the validity of steady-state transport analysis in these systems. Nilanjan Bondyopadhaya and Dibyendu Roy try to find a solution to the above important issue for the very first time.

The time dependent orbital diamagnetic moment of a charged particle in a magnetic field in a viscous medium was investigated during the past year via the Quantum Langevin Equation by Urbashi Satpathi and Supurna Sinha. The predictions resulting from the study can be tested via state-of-the-art cold atom experiments with hybrid traps for ions and neutral atoms.

Classical and Quantum gravity

A quantum theory of spacetime merges General Relativity with Quantum Theory. Such a theory could help resolve some of the fundamental puzzles about our universe, like dark energy and the black hole information puzzle, as well as resolve the singularities of General Relativity. However, merging the two theories has proved to be a very difficult task. At RRI two different approaches to this problem are currently being pursued, Loop Quantum Gravity and 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').

In the early days of LQG, Thiemann proposed that dynamical solutions of Lorentzian LQG could be obtained by a 'Wick' transformation of those of Euclidean LQG. This transformation is generated by a certain Wick rotation operator. During the past year, Madhavan Varadarajan re-considered Thiemann's proposal in the light of subsequent developments, introduced and advocated the use of a new positive Wick rotator and suggested a quantum Hilbert Space arena for its definition. Since his recent work on the Hamiltonian constraint suggests avenue for progress in Euclidean LQG, this work, in turn re-examines how such progress in the Euclidean theory could directly feed into the definition of Lorentzian LQG.

Due to an influential paper by Smolin in the 90's, a folklore has developed in the field that quantum dynamics in LQG constructions are not consistent with the propagation of perturbations. Within the simple context of a 2d field theory, Madhavan Varadarajan showed a few years ago that this folklore is wrong and that LQG constructions there can lead to propagating dynamics. The model studied, however, was vastly simpler than gravity and it is desirable that a demonstration of propagation be available for more complex systems closer to gravity. In this regard, Madhavan's current work demonstrates that LQG methods applied to the immensely more complex system of weakly coupled Euclidean Gravity can result in propagation.

Causal Set Theory

A manifestly covariant approach to quantum gravity is Causal Set Theory (CST). CST is motivated by deep theorems in Lorentzian geometry that demonstrate the primacy of the causal structure of spacetime. The causal structure of any reasonable spacetime forms what is known as a partially ordered set. Rather than quantize the geometry, in CST one quantizes this causal structure. The spacetime continuum is thus replaced by a discrete substructure, which is a locally finite partially ordered set or causal set. A striking phenomenological consequence of the mixture of discreteness and causality is Sorkin's

prediction for the cosmological constant several years before it was confirmed by observation.

One of the challenges in CST is to recover the continuum spacetime geometry from order invariants. While several topological and geometric invariants are known, it has been difficult to obtain spatial information. In recent work at the Institute, Sumati Surya along with collaborators Astrid Eichhorn, Fleur Versteegen have obtained a spatial induced distance function on the analogue of a space like hypersurface using just the ambient causal relations. This gives a new class of observables for the theory.

CST discretization is also a promising way to regulate the infinities of QFT. However, the standard tools of QFT use the non-covariant slicing of spacetime. This leads to the lack of a preferred QFT vacuua in generic curved spacetimes. As was pointed out by Hawking and subsequently Unruh, the choice of vacuum and thence the particle content depend on the observer and is not therefore covariantly defined. The Pierels bracket formulation of QFT is well suited to CST discretization. Using this, Sorkin and Johnston constructed a unique covariant ground state, the SJ vacuum for Klein-Gordon fields. Studies of the SJ vacuum have shown interesting departures from the standard QFT. Using a causal set discretization of a slab of 2d and 4d de Sitter spacetime, Nomaan X and Sumati Surya along with collaborator Yasaman Yazdi obtained the causal set SJ vacuum for a range of masses. Their results hint at an important tension between the discrete and continuum behavior of the SJ vacuum in de Sitter and suggests that the former cannot in general be identified with the Mottola-Allen α-vacua. In related work, Abhishek Mathur and Sumati Surya have analytically studied the 2d massive SJ vacuum in flat spacetime, and have found regimes in which it coincides with the standard vacuum.

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.

Supurna Sinha and Joseph Samuel in collaboration with Arpita Maitra investigated the issue of quantum state determination by 'tossing' a quantum coin and found that quantum entanglement leads to an improved strategy in state determination compared to one where a string of qubits were measured individually. They demonstrated this on the simulation facility of IBM quantum computers.

In spite of extensive studies, the origin of uniform acceleration and non-spreading of wavepackets that propagate in free particle Schrodinger equation was not clear. Vivek Vyas has recently shown that these peculiar properties have their origin in the fact that these wavepackets are (Perelomov) coherent states and that the Galilean invariance of the free particle Schrodinger equation plays a pivotal role in giving these coherent states their unique dynamical property. His current efforts are focused towards generalizing this work from closed to open quantum systems and to higher spatial dimensions.

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 that 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 2018-19

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 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. For example, two structures in the form of bubbles were seen to emanate outwards from the center of our Milky Way galaxy, pointing towards very energetic and ongoing event in the center region of the Milky Way. 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 2018-19 follows.

Galactic Outflows

Gaseous outflow from star forming galaxies

With Eugene Vasiliev and Yuri Shchekinov, Biman Nath has been trying to study the threshold Star Formation Rate (SFR) required to launch gaseous outflows, and compare it with observations. Detailed simulations in which they varied SFR, gas density and gas scale height, led to the deduction of a threshold energy injection rate density, which compares well with observations. This work has been published in MNRAS.
[Eugene O. Vasiliev (Southern Federal University, Russia), Yuri A. Shchekinov (Lebedev Physical Institute of Russian Academy of Sciences, Russia) and Biman Nath]

Cosmic rays from superbubbles

Siddhartha Gupta has worked out various observational effects of cosmic rays emanating from superbubbles, in gamma-rays, X-rays and in radio wavelengths. After comparing with observations, Siddhartha Gupta and Biman Nath along with collaborator Prateek Sharma have identified the wind termination shock as the site of cosmic ray acceleration.
[Siddhartha Gupta, Biman Nath and Prateek Sharma (Indian Institute of Science, Bengaluru)]

Cosmic rays from Superbubbles—isotope ratio

During the past year, Biman Nath, Siddhartha Gupta and collaborator Prateek Sharma have been working on the

implications of superbubbles being sites of cosmic ray acceleration, with regard to Neon (22 to 20) isotope ratio. They are collaborating with David Eichler, an authority on cosmic ray acceleration, on this topic. This important piece of work is currently being prepared for submission to a journal.
[Biman Nath, Siddhartha Gupta, Prateek Sharma (Indian Institute of Science, Bengaluru) and David Eichler (Ben-Gurion University of the Negev, Israel)]

Extra-planar radio emission from star forming disc galaxies

During 2018-19, Aditi Vijayan has performed detailed Magneto-HydroDynamic (MHD) simulations of star forming galaxies, with star formation sites distributed in a disc, in order to simulate the radio halo around galaxies. Aditi Vijayan and Biman Nath hope to compare the simulated radio maps with observed maps from edge-on star formation galaxies, and infer the physics behind synchrotron radio halos.
[Aditi Vijayan and Biman Nath]

Resonant transport of angular momentum in galaxies

Stalling of globular cluster orbits in dwarf galaxies

A globular cluster orbiting a dwarf galaxy is expected to in-spiral to the center of the galaxy within the age of the Universe, according to the Chandrasekhar dynamical friction formula. But many dwarf galaxies host globular clusters well away from their centers, and this has been a dynamical puzzle since the 1970s. It has long been suspected that the Chandrasekhar formula fails in the cores of dwarf galaxies (i.e. within a few hundred parsecs from the center). The manner of its failure has been investigated by numerical simulations but a dynamical explanation has been absent. During 2018-19, K Kaur and S Sridhar have provided a dynamical explanation by using the theory of dynamical friction due to Tremaine & Weinberg (1984), wherein the retarding torque ('drag') on the globular cluster by stars is exerted by stars whose orbital frequencies are in resonance with the globular cluster's orbit, and given as a sum over the infinitely many resonances. Since the difficulty in applying the theory is to calculate the resonant torques, of which there are very many of comparable strengths, they classified families of resonances, identified more than 200 strong resonances, and calculated their torques as functions of the globular cluster's radial location in the galaxy. Summing over the resonant torques gave the net retarding torque on the globular cluster, as a function of its location. This was smaller than the Chandrasekhar torque by factors of 100 to 10,000. Integrating the equations of motion, they determined the orbital decay of the globular cluster, which stalled as reported in numerical simulations. This could possibly be the first physical and quantitative solution of the 'dynamical friction problem'. This work has been published in The Astrophysical Journal.
[K Kaur and 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.

A two population electron synchrotron model for knots of extended jets

Radio observations by Atacama Large Millimeter Array (ALMA) and upper limits on gamma ray flux by Fermi Large Area Telescope (Fermi LAT) have ruled out inverse Compton scattering of Cosmic Microwave Background radiation by relativistic electrons (IC/CMB) as the origin of X-ray emission from extended jets of six quasars 3C 273, PKS 0637-752, PKS 1136-135, PKS 1229-021, PKS 1354+195, and PKS 2209+080. During the past year a two population electron synchrotron model for knots of extended jets was suggested by Nayantara Gupta and collaborator Samaresh Mondal. They considered two populations of accelerated electrons in each knot of the extended jets to explain the radio to optical and the X-ray emission by synchrotron cooling of relativistic electrons. In all cases the jet power required was found to be lower than the Eddington's luminosity and the observed knot emissions were well explained in this scenario. This work has now been published. (Astropart. Phys. 107 (2019) 15)
[Samaresh Mondal (NCAC, Poland) and Nayantara Gupta]

Ultrahigh energy cosmic rays and neutrinos from light nuclei composition

The baryonic mass composition of ultrahigh energy (10^{18}eV) cosmic rays (UHECRs) at injection accompanied by their interactions on universal photon backgrounds during propagation directly governs the UHECR flux on the Earth. Secondary neutrinos and photons produced in these interactions serve as crucial astrophysical messengers of UHECR sources. A modeling of the latest data obtained by the Pierre Auger Observatory (PAO) suggests a mixed element composition of UHECRs with the sub-ankle spectrum being explained by a different class of sources than the super-ankle region ($> 10^{18.7}$ eV).

In recent work at RRI, Saikat Das, Nayantara Gupta along with collaborator Soebur Razzaque have obtained two kinds of fit to the UHECR spectrum – one with a single population of sources comprising of 1H and 2He, over an energy range commencing at 10^{18} eV – another for a mixed composition of representative nuclei 1H, 4He, 14N and 28Si at injection, for which a fit is obtained from above $10^{18.7}$eV. In both cases, the source emissivity evolution was considered to be a simple power-law in redshift and the credibility of H+He composition was tested by varying the source properties over a wide range of values and comparing the results to that obtained for H+He+N+Si composition, using the Monte Carlo simulation tool CRPropa 3. They propagated the secondary electrons and photons using the cosmic ray transport code DINT and placed limits on the source spectral index, source evolution index and cutoff rigidity of the source population in each case, by fitting the UHECR spectrum. It was observed that cosmogenic neutrino fluxes can further constrain the abundance fraction and maximum source redshift in case of light nuclei injection model. This work led to a publication. (Phys. Rev. D 99 (2019) 083015)
[Saikat Das, Soebur Razzaque(University of Johannesburg, South Africa) and Nayantara Gupta]

Two-zone emission modeling of PKS1510-089 during the high state of 2015

PKS 1510-089 is one of the most variable blazars in the third Fermi LAT source catalog. During 2015, this source had shown four major flares identified as flare A, B, C, and D in between three quiescent states Q1, Q2, and Q3. Using multi-wavelength data from Fermi-LAT, Swift-X-Ray Telescope(XRT)/Ultraviolet Optical Telescope (UVOT), Owens Valley Radio Observatory (OVRO), and Sub-millimeter array (SMA) Observatory, Raj Price, Nayantara Gupta and collaborator Krzysztof Nalewajko have modelled these states and inferred the following: Different variability times in different energy bands indicates there could be multiple emission zones. The variability time from the gamma-ray light curve was found to be 18.32 hr, from the X-ray light curve it was found to be 3.7 days, and its average variability time in the optical/UV band was 1.5 days. It could be possible that the gamma-ray and optical/UV emission are produced in the same region whereas X-ray emission could be coming from a different region along the jet axis. They have also estimated the discrete correlations function (DCFs) among the light curves of different energy bands to infer about their emission regions. Their DCFs analysis showed zero time lag between the gamma-ray and optical/UV emission indicating their co-spatial origin, whereas a time lag of around 50 days found between gamma-ray and X-ray light curves indicates that these two emission are from different regions. Motivated by these inferences, a two-zone multi-wavelength time-dependent modeling with one emission zone located near the outer edge of the broad line region (BLR) and another further away in the dusty/molecular torus (DT/MT) region was performed.
[Raj Prince, Nayantara Gupta and Krzysztof Nalewajko (Nicolaus Copernicus Astronomical Center, Warsaw, Poland)]

Study of isotropic gamma ray background (IGRB) using cosmic ray spectra

During 2018-19, Sayan Biswas and Nayantara Gupta considered a realistic galactic magnetic field model and density profiles of gaseous components of interstellar medium (ISM) and used the DRAGON code to get proton (p) distribution in the ISM by fitting the observed spectra of p, B/C and 10Be/9Be at the position of the Sun. Subsequently, the obtained proton spectrum in the ISM and the total gas density profile of ISM were used to calculate Isotropic Diffuse Gamma Ray Background (IGRB) from p-p collisions. Upon comparing the IGRB spectrum above galactic latitude $|b| > 20$ degree with the IGRB spectrum measured by Fermi-LAT they found that the obtained IGRB spectrum was consistent with the Fermi- LAT observation.
[Sayan Biswas and Nayantara Gupta]

Cosmology

Dipole Anisotropy as an Essential Qualifier for the Monopole Component of the Cosmic-dawn Spectral Signature, and the Potential of Diurnal Pattern for Foreground Estimation

While the importance of detecting the global spectral signatures of the redshifted 21 cm line of atomic hydrogen from the very early epochs cannot be overstated, the associated challenges are not limited to isolating the weak signal of interest from the orders of magnitude brighter foregrounds, and extend equally reliably establishing the origin of the apparent global signal to the very early epochs.

Avinash Deshpande has proposed a critical dipole test that the measurements of the monopole component of the spectrum of interest should necessarily pass. His criterion is based on a unique correspondence between the intrinsic monopole spectrum and the differential spectrum as an imprint of dipole anisotropy (DA) resulting from the motion of observer with respect to the rest frame of the source (such as that of our solar system, interpreted from the DA in the cosmic microwave background radiation (CMBR)). More importantly, the spectral manifestation of the DA gets amplified by a significant factor, depending on the monopole spectral slopes, rendering it feasible to measure. He further describes the details of such a test, and

has illustrated its application with the help of simulations. He also alludes to a novel model-independent path toward isolating the foreground contribution, using the diurnal pattern readily apparent in drift-scan observations. Such a dipole qualifier for the monopole spectrum, when combined with reliable foreground estimation, is expected to pave way for in situ validation of spectral signatures from early epochs, which are important to presently reported and future detections of Epoch of Reionization (EoR) signal. Further exploration for isolating the foreground contribution, based on the diurnal pattern, is in progress.

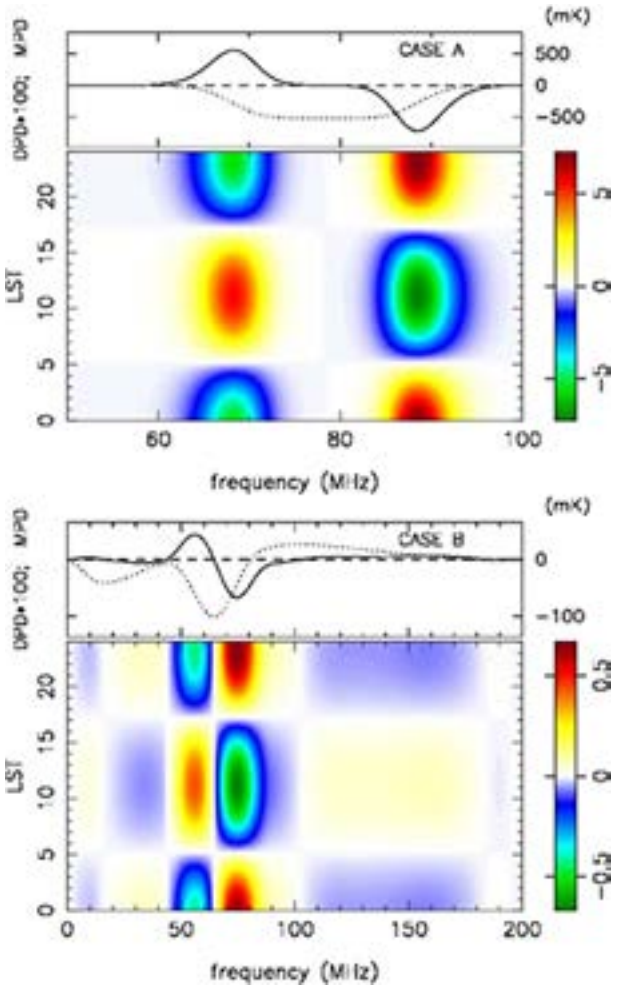


Figure 1. Expected set of residual or difference spectral profiles across the entire LST range, after subtraction of the "all-sky" average spectral profile from the simulated set containing the discussed mild dipole frequency modulation, are shown. The 24 hr cycle and the correspondence with the first (spectral) derivative of the assumed underlying monopole spectrum are clearly evident. The amplitude of the co-sinusoidal variation (solid line), after scaling up by 100, is shown in the top panel for each case A and B, along with the assumed monopole spectrum (dotted line). The cases A and B correspond, respectively, to BR3M18 best-fit profile (50–100 MHz) and the much discussed theoretically predicted spectrum up to 200 MHz (the "turning points" data taken from Pritchard & Loeb 2012).

[Avinash Deshpande]

Analytically modelling the early phase of reionization

It is hard to study the epoch of reionization numerically owing to the diversity of length scales in the problem. Many semi-analytic methods, e.g. self-ionized regions, are used to model this era. Janakee Raste and Shiv Sethi have attempted to model the early phase (before ionization inhomogeneities begin to dominate) of reionization analytically using a formulation suitable for statistical detection of the HI signal. They have shown that the early phase, which is dominated by heating, Lyman-α and/or density inhomogeneity, can be studied using topological properties of the heated/Lyman-α coupled regions. Modeling this era using three parameters that represent ionization, heating, and Lyman-α radiation fields has showed that this entire phase ($10 < z < 30$) can be modelled by a single function of four variables. Their results are in reasonable agreement with existing numerical results (Figure 2 and 3).

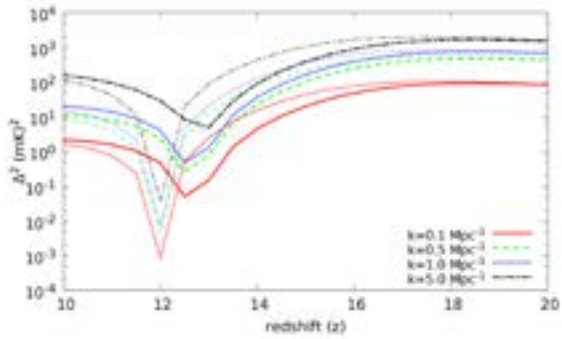


Figure 2. Evolution of $\Delta^2 = k^3P(k)/2\pi^2$ $((mK)^2)$ is displayed as a function of redshift for a range of scales k; P(k) is the power spectrum of the spatial distribution of HI gas. The signal is displayed for a fixed spectral index of radiation $\alpha = 1.5$ and common ionization history. The thick curves are for νmin = 100 eV, where νmin is the smallest frequency responsible for heating the medium, and the thin curves are for νmin = 1 keV.

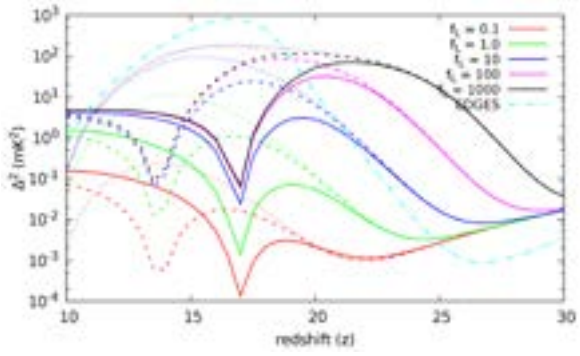


Figure 3. Evolution of $\Delta^2 = k^3P(k)/2\pi^2$ $((mK)^2)$ is displayed as a function of redshift for $k = 0.125$ Mpc^{-1}. The figure shows the impact of Lyman-α and heating inhomogeneities for $z < 30$. The Lyman-α parameter fL varies from 0.1 to 1000 for three values of heating parameter Nheat: 10 (solid lines), 1 (long-dashed curves) and 0.1 (short-dashed curves). The dot-dashed line shows the fiducial model that matches with EDGES observation.

[Janakee Raste and shiv Sethi]

Magnetic breaking and direct collapse primordial black holes

The presence of supermassive black holes at z ≃7 remains an enigma. These black holes could have formed through accretion on stellar mass black holes formed at z > 10 but the accretion rates are not high enough to enable the formation of such massive black holes. One possible way out of this situation is to posit that the first black holes were far more massive than stellar black holes, which can be achieved in direct collapse black hole (DCBH) scenario. Shiv Sethi and collaborators Kanhaiya Pandey and Bharat Ratra have proposed a mechanism to enable such collapse in haloes of masses > 10^7 $M_\odot$ by proposing that primordial magnetic fields could have provided the mechanism to remove angular momentum, an essential ingredient for spherical collapse, from these haloes. They studied an analytic model and have shown that the strength of the magnetic field needed to achieve spherical collapse are consistent with existing bounds.
[Kanhaiya Pandey (IIA, Bangalore), Shiv Sethi and Bharat Ratra (KSU, USA)]

Impact of primordial black holes on reionization era

The cosmological implications of the formation of the first stellar size black holes (BHs) in the universe was studied by Shiv Sethi and collaborators. They considered three possible observables from the influence zones around accreting BHs during 8.5 < z < 25: the H I 21 cm line, the hyperfine line of 3He II, and the H I recombination lines and showed that the 21 cm emitting region around a growing BH could produce brightness temperatures

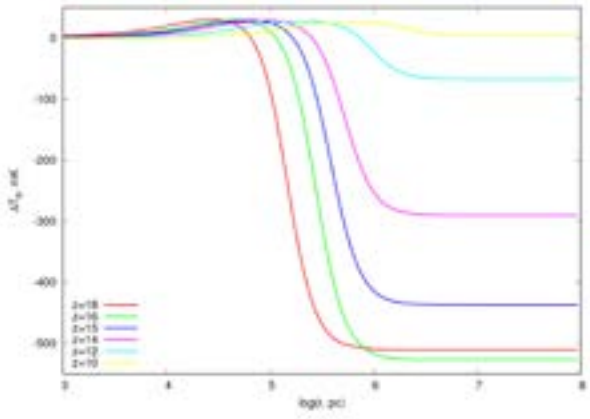


Figure 4. The brightness temperature in the 21 cm HI line is shown as a function of radius around a black hole with initial mass M_{BH} = 300 $M_\odot$ at z_0 = 40. The altered thermodynamics of baryons due to elastic scattering with cold dark matter as implied by EDGES results are taken into account.

15 mK across an evolving structure of 1 Mpc 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 Low Frequency Array (LOFAR) and the Square Kilometre Array (SKA) SKA1-LOW might be able to detect these regions. They have further shown that for growing BHs, the Hα line could be detected by the James Webb Space Telescope with a signal-to-noise ratio of 10 in 10^4 seconds of integration. In light of the recent result of the Experiment to Detect the Global EoR Signature (EDGES), they have shown that with additional cooling of baryons owing to collision with dark matter, the H I signal could be enhanced by more than an order of magnitude (Figure 4).
[Eugene Vasilliev (Rostov university, Russia), M. V. Ryabova (Rostov university, Russia), Yuri Schechinov (Lebedev Institute, Russia) and Shiv Sethi]

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

A study of spectral curvature in the radio relic in Abell 4038 using the uGMRT

The remnant radio galaxies in galaxy clusters are important sources of seed relativistic electron population in the intracluster medium (ICM). Their occurrence and spectral properties are poorly studied. During the past year, Viral Parekh, K S Dwarakanath and collaborator Ruta Kale conducted a broad-band study of the radio relic in the galaxy cluster Abell 4038 using the Upgraded Giant Metrewave

Radio Telescope (uGMRT). They have presented the uGMRT images in the bands 300-500 MHz and 1050-1450 MHz having rms noise 70 and 30 μJy beam^{-1}, respectively, that are the deepest images of this field so far. A spectral analysis of the relic over 300-1450 MHz using images in sub-bands scaled to have constant fractional bandwidths to achieve a closely matched UV-coverage was carried out. The 100 kpc extent of the relic is divided into Loop, Arc, Bridge, and North-end. The Loop has a steep spectral index of $\alpha = 2.3 \pm 0.2$ ($S \propto \nu^{-\alpha}$). The North- end has ultra-steep spectra in the range 2.4-3.7. The Arc was found to skirt a curved region seen in the Chandra X-ray surface brightness image and the highest spectral curvature in it reaches 1.6 ± 0.3. They interpret the morphology and spectral properties of the relic in the scenario of an adiabatically compressed cocoon from the past activity of the brightest cluster galaxy in the cluster. A comparison of the properties of the A4038 relic with a sample of 10 such relics also formed part of the study.
[Ruta Kale (National Centre for Radio Astronomy, TIFR, Pune), Viral Parekh and K S Dwarakanath]

Local pulsar monitoring and Search for fast transients with Gauribidanur telescope

Monitoring of local pulsars, to study variability in their properties and that of the intervening medium, is continued. Targeted observations to search for pulsars and fast transients are also on-going at 34.5 MHz, using the Gauribidanur Radio Telescope.
[H A Aswathappa and Avinash Deshpande]

A multi-frequency study of drifting subpulses of B0809+74

Through improved pulsar data analysis which includes packet synchronization, estimating dynamic spectra for both polarizations, RFI detection and subsequent rejection of the data, de-compression, de-dispersion and obtaining time series, Avinash Deshpande and collaborator Hrishikesh Shetgaonkar obtained single pulse stacks for pulsar B0809+74 using data obtained from the RRI-GBT Multi-Band Receiver on the Green-Bank Telescope. These single pulse stacks were then analyzed to estimate the sub-pulse drift parameters P3 ~ 11 periods and P4 ~ 207 periods. Subsequently, a P3 and P4 folded drift profile was obtained. The analysis was performed for mainly three bands (172, 230 and 330 MHz), where the pulses were seen with high signal-to-noise ratio. A detailed analysis of the drift pattern suggests a system of 19 sub-beams rotating around the magnetic axis of pulsar B0809+74.
[Avinash Deshpande and Hrishikesh Shetgaonkar (BITS-Pilani)]

Galactic distribution of pulsars

During the past year, efforts were towards studying the distribution of pulsars, and assessment of underlying processes which govern their distribution.
[Aleena Baby and Avinash Deshpande]

On the Geometry of Curvature Radiation and Implications for Subpulse Drifting

The phenomenon of subpulse drifting offers unique insights into the emission geometry of pulsars, and is commonly interpreted in terms of a rotating carousel of spark events near the stellar surface. Avinash Deshpande along with collaborators S. J. McSweeney, N. D. R. Bhat, S. E. Tremblay and G. Wright has developed a detailed geometric model for the emission columns above a carousel of sparks that is entirely calculated in the observer's inertial frame, and which is consistent with the well-understood rotational effects of aberration and retardation. They also explored the observational consequences of the model, including (1) the appearance of the reconstructed beam pattern via the cartographic transform, and (2) the morphology of drift bands and how they might evolve as a function of frequency. The model, implemented in the software package PSRGEOM, is applicable to a wide range of viewing geometries, and they have illustrated its implications using PSRs B0809+74 and B2034+19 as examples. Some specific predictions were made with respect to the difference between subpulse evolution and microstructure evolution, which provides a way to further test the model.
[S. J. McSweeney (Curtin University, Australia), N. D. R. Bhat (Curtin University, Australia), S. E. Tremblay (Curtin University, Australia), G. Wright (UK) and Avinash Deshpande]

Dynamic spectral signatures of Lunar Occultation: A simulation study

Lunar occultation, which occurs when the Moon crosses sight-lines to distant sources, has been studied extensively through apparent intensity pattern resulting from Fresnel diffraction, and has been successfully used to measure angular sizes of extragalactic sources. However, such observations till date have been mainly over narrow bandwidth, or averaged over the observing band, and the associated intensity pattern in time has rarely been examined in detail as a function of frequency over a wide band. Jigisha Patel and Avinash Deshpande have revisited the phenomenon of lunar occultation with a view to study the associated intensity pattern as a function of both time and frequency. Through analytical and simulation approach, they have examined the variation of intensity across the dynamic spectra, and looked for chromatic

signatures which could appear as discrete dispersed signal tracks, when the diffraction pattern is adequately smoothed by a finite source size. They have particularly explored circumstances in which such diffraction pattern might closely follow the interstellar dispersion law followed by pulsars and transients, such as the Fast Radio Bursts, which remain a mystery even after a decade of their discovery. In a paper published during the past year, they describe details of this investigation, relevant to radio frequencies at which FRBs have been detected, and discuss their findings, along with their implications. They also show how a band-averaged light curve suffers from temporal smearing, and consequent reduction in contrast of intensity variation, with increasing bandwidth. Further, they suggest a way to recover the underlying diffraction signature, as well as the sensitivity improvement commensurate with usage of large bandwidths.
[Jigisha Patel and Avinash Deshpande]

Diffuse matter in galaxies

As mentioned in the previous annual report, Chandrasekhar Murugesan, Geethu Paulose and Ramesh Balasubrahmanyam have been investigating the relation between metallicity and the initial mass function (IMF) slope. They had evolved proxy measures for bulk gas-phase metallicity which correlates well with measured (O/H) metallicities for late type galaxies. They tested the IMF slope proxy against the measured metallicities to find a negative correlation. The reasonably strong and tight correlation between the proxies indicated that metallicity is indeed a key driver of IMF slope in late type galaxies. The metallicity proxy relation can be inverted to estimate S_{HI} and S_{CO} for galaxies with measured metallicity and NIR flukes. This would be especially useful for intermediate redshift galaxies where direct measurements are time consuming.

Given these new tracers, during the past year they investigated how they change among galaxies showing different dynamical states as reflected by the number of arms or their rotational speeds reflecting their dark-matter mass. A set of galaxies from the Galaxy zoo catalog were chosen and relevant data were collected from the literature. Unfortunately, a statistically significant set with relevant data in these categories could not be obtained. The manuscript reporting this work is being submitted to a refereed journal.
[Chandrasekhar Murugesan, Geethu Paulose and Ramesh Balasubrahmanyam]

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. A brief overview of various aspects of compact X-ray sources investigated by RRI astronomers during 2018-19 is given below.

Investigation of various aspects of compact X-ray sources

Probing the Cyclotron line characteristics of 4U 1538-522 using AstroSat-LAXPC

During 2018-19, Varun and Biswajit Paul along with collaborators Chandreyee Maitra, Pragati Pradhan and Harsha Raichur have made the first report on cyclotron line studies with the LAXPC instrument onboard AstroSat - of a high-mass X-ray binary pulsar 4U 1538-52. During the observation of source that spanned about 1 day with a net exposure of 50 ks, the source X-ray flux remained constant. They found the pulse profile to be double peaked in low-energy range and single peaked in high-energy range with the transition taking place around the cyclotron line energy of the source. Cyclotron scattering feature (CRSF) was detected at ~22 keV with a very high significance in phase-averaged spectrum. This is one of the highest signal to noise ratio detections of CRSF for this source. Further, they performed detailed pulse-phase-resolved spectral analysis with 10 independent phase bins and reported the results of pulse-phase-resolved spectroscopy of the continuum and CRSF parameters. The cyclotron line parameters showed pulse phase dependence over the entire phase with a CRSF energy variation of ~13%, in agreement with previous studies. Additionally, they confirmed the increase in the centroid energy of the CRSF observed between the 1996-2004 (RXTE) and the 2012 (Suzaku) observations, reinforcing that the increase was a long-term change.
[Varun, Chandreyee Maitra (Max Planck Institute For Extraterrestrial Physics, Germany), Pragati Pradhan (Pennnsylvania State University, USA and St Joseph's College, Darjeeling), Harsha Raichur (KTH Royal Institute of Technology, Sweden) and Biswajit Paul]

Pulse Phase Variation of Cyclotron Line in HMXB 4U 1907+09 with AstroSat-LAXPC

The above team also carried out a timing and spectral analysis of data from an observation of the High Mass X-ray Binary pulsar 4U 1907+09 with the LAXPC instrument onboard AstroSat. The light curve consisted of a flare at the beginning of the observation followed by persistent emission. The analysis revealed the pulsar continued its spin down, and the pulse profile was found to be double-peaked up to 16 keV with the peaks separated by a phase of ~0.45. Significant energy dependence of the pulse profile was seen with diminishing amplitude of the secondary peak above 16 keV, and increasing amplitude of the main peak upto 40 keV with a sharp decline after that. Further, they have detected the Cyclotron Resonance Scattering Feature (CRSF) in 4U 1907+09 to be at ~18.5 ± 0.2 keV in the phase-averaged spectrum with a high detection significance. An intensity resolved spectral analysis of the initial flare in the light curve showed that the CRSF parameters do not change with change in luminosity by a factor of 2.6. The LAXPC observation increases the luminosity range over which the CRSF has been detected in 4U 1907+09 without any clear indication of a luminosity dependence. Additionally, they performed pulse phase-resolved spectral analysis with ten independent phase bins which showed that the energy and the strength of the cyclotron line showed pulse phase dependence that is in agreement with previous measurements. Two features from their study: (i) different energy dependence of the two pulse peaks and (ii) a strong CRSF only around the secondary peak, both indicate a deviation from a dipole geometry of the magnetic field of the neutron star, or complex beaming pattern from the two poles.
[Varun, Chandreyee Maitra (Max Planck Institute for Extraterrestrial Physics, Germany), Pragati Pradhan (Pennnsylvania State University, USA and St Joseph's College, Darjeeling), Harsha Raichur (KTH Royal Institute of Technology, Sweden) and Biswajit Paul]

Thermonuclear X-ray bursts in rapid succession in 4U 1636-536 with AstroSat-LAXPC

In yet another study using ASTROSAT-LAXPC, Biswajit Paul and collaborators reported results from an observation of the low-mass X-ray binary 4U 1636-536. Their observations made during the performance verification phase of AstroSat showed seven thermonuclear X-ray bursts in a total exposure of ~65 ks over a period of about two consecutive days. Moreover, the light curve of 4U 1636-536 revealed the presence of a rare triplet of X-ray bursts, having a wait time of about 5.5 min between the second and the third bursts. They also presented results from time-resolved spectroscopy performed during these seven X-ray bursts. In addition, they have also detected a transient quasi-periodic oscillation at ~5 Hz. However, no evidence of kilo-hertz quasi-periodic oscillations and/or X-ray burst oscillations was found, which they attribute to the hard spectral state of the source during this observation.
[Aru Beri (IISER-Mohali & Southampton University, UK), Biswajit Paul, J. S. Yadav (TIFR, Mumbai), H. M. Antia (TIFR, Mumbai), P. C. Agrawal (University of Mumbai), R. K. Manchanda (University of Mumbai), Dhiraj Dedhia (TIFR, Mumbai), Jai Verdhan Chauhan (TIFR, Mimbai), Mayukh Pahari (Southampton University, UK), Ranjeev Misra (IUCAA, Pune), Tilak Katoch (TIFR, Mumbai), P. Madhawani (TIFR, Mumbai), P. Shah (TIFR, Mumbai), Varun, Sujay Mate (RRI & Université de Toulouse, CNRS, France)]

Detection of multitude of iron lines including a Compton-scattered component in OAO 1657-415 with Chandra

Studies of the high-resolution X-ray spectrum of the accreting X-ray pulsar OAO 1657-415 obtained with HETG + ACIS-S onboard Chandra by RRI astronomers Gayathri Raman and Biswajit Paul along with collaborator Pragati Pradhan has revealed the presence of a broad line component around ~6.3 keV associated with the neutral iron K_α line at 6.4 keV. They interpret this as a Compton shoulder arising from the Compton-scattering of the 6.4-keV fluorescence photons, making OAO 1657-415 the second accreting neutron star in which such a feature has been detected. A Compton shoulder reveals the presence of dense matter surrounding the X-ray source. They did not detect any periodicity in the light-curve and obtained an upper limit of ~2 per cent for the pulse fraction during this observation which could be a result of the smearing of the pulses when X-ray photons are scattered from a large region around the neutron star. In addition to the Fe K_α, Fe K_β and Ni K_α lines already reported for this source, this study reports for the first time the presence of He-like and H-like iron emission lines at 6.7 and 6.97 keV in the first-order HETG spectrum. The detection of such ionized lines, indicative of a highly ionized surrounding medium, is rare in X-ray binaries.
[Pragati Pradhan (Pennnsylvania State University, USA, and St Joseph's College, Darjeeling), Gayathri Raman (ICTS) and Biswajit Paul]

Detection of a cyclotron line in SXP 15.3 during its 2017 outburst

Biswajit Paul and collaborators carried out a study of the transient Be/X-ray binary pulsar SXP 15.3 in the Small Magellanic Cloud during its outburst in late 2017 with AstroSat and NuSTAR observations, when the source reached a luminosity level of ~10^{38} erg s^{-1}, close to the Eddington limit. The unprecedented broad-band coverage

of the source allowed them to perform timing and spectral analysis between 3 and 80 keV. The pulse profile was seen to exhibit a significant energy dependence, and morphed from a double-peaked profile to a single broad pulse at energies >15 keV which they explained by a spectral hardening during an intensity dip seen between the two peaks of the pulse profile. They further detected a Cyclotron Resonance Scattering Feature at ~5 keV in the X-ray spectrum, independent of the choice of the continuum model which indicates a magnetic field strength of 6×10^{11} G for the neutron star.
[Chandreyee Maitra (Max Planck Institute for Extraterrestrial Physics, Germany), Biswajit Paul, Frank Haberl (Max Planck Institute for Extraterrestrial Physics, Germany), and G. Vasilopoulos (Max Planck Institute for Extraterrestrial Physics, Germany)]

X-ray reprocessing through the eclipse spectra of High Mass X-ray Binaries with XMM-Newton

The study of X-ray reprocessing is one of the key diagnostic tools to probe the environment in X-ray binary systems. One difficult aspect of studying X-ray reprocessing is the presence of much brighter primary radiation from the compact star together with the reprocessed radiation. In contrast, for eclipsing systems, the X-rays received during eclipse are only those produced by reprocessing of the emission from the compact star by the surrounding medium.

During 2018-19, Nafisa Aftab, Biswajit Paul and collaborator Peter Kretschmar reported results from a spectral study of the X-ray emission during eclipse and outside eclipse (when available) in 9 high mass X-ray binaries (HMXBs) with XMM-Newton to investigate different aspects of the stellar wind in these HMXBs. During eclipse, the continuum component of the spectrum was found to be reduced by a factor of ~8–237, but the flux of the 6.4 keV iron emission line or complex of iron emission lines in HMXBs were reduced by a smaller factor leading to large equivalent widths of the Iron emission lines. This is indicative of a large size for the line emission region which is comparable to or larger than the companion star in these HMXB systems. However, significant system to system differences were observed. 4U 1538−52, in spite of having a large absorption column density, showed a soft emission component with comparable flux during the eclipse and out-of-eclipse phases. Emission from hydrogen-like Iron has been observed in LMC X-4 for the first time, in the out-of-eclipse phase in one of the observations. Overall, significant differences were found in the eclipse spectrum of different HMXBs and also in their eclipse spectra against out-of-eclipse spectra.
[Nafisa Aftab, Biswajit Paul, and Peter Kretschmar (ESA-ESAC, Madrid, Spain)]

Cosmological implications of the composite spectra of galactic X-ray binaries constructed using MAXI data

In a collaborative effort, RRI astronomer Biswajit Paul, RRI astrophysicist Biman Nath along with national and international peers have investigated the long term average spectral properties of galactic X-ray binaries in the energy range of 3–20 keV, using long term monitoring data from MAXI–Gas Slit Camera (GSC). They used the long term average spectra to construct separately the composite spectra of galactic High Mass X-ray Binaries (HMXBs) and Low Mass X-ray Binaries (LMXBs). These composite spectra were described empirically with piece wise power-law with three components. They considered X-rays from HMXBs as important contributors to heating and ionization of neutral hydrogen in the inter- galactic medium during the Epoch of Reionization. Using the above empirical form of the composite HMXB spectra extrapolated to lower energies as an input, they studied the impact of these sources on the 21-cm signal using the outputs of N-body simulation and 1D radiative transfer. The heating due to the composite spectrum was found to be less patchy compared to power-law spectrum with a spectral index $\alpha = 1.5$, used in previous studies while the amplitude of the heating peak of large scale power spectrum, when plotted as a function of the redshift, was found to be less for the composite spectrum.
[Nazma Islam (CfA, Harvard & Smithsonian, USA), Raghunath Ghara (Stockholm University, Sweden), Biswajit Paul, T. Roy Choudhury (NCRA) and Biman B. Nath]

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, 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.

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 2018-19, significant progress has been made in making the Qualification Model of POLIX and fabrication of some of the Flight Model components of POLIX has been initiated. The MOU between RRI and ISRO for POLIX onboard XPoSat was revised and second phase of funding for POLIX was released to initiate the Flight Model of POLIX.

- Preliminary Design Review (PDR) of the XPoSat Satellite including the POLIX payload was conducted successfully in ISRO in September 2018.
- Design of all flight electronics cards have been completed.
- Space qualified layout, layout review, and fabrication of the same have been initiated.
- The mechanical design of POLIX has been revised with input from the preliminary design review.
- Finite element modelling and analysis of the revised mechanical design of POLIX have been completed and reviewed.
- Fabrication of the FM mechanical elements of POLIX is in progress.
- Preliminary collimator calibration has been carried out for angular response and off-axis response.
- Ground checkout system for POLIX has been developed.
- Significant progress has been made in software development for POLIX data reduction and analysis.

[Biswajit Paul, P. V. Rishin, M. R. Golapakrishna, S. Krishnamurthy, Md Ibrahim, Abhilash Kulkarni, Pooja Verma, G. Rajagopala, Aditya Murumkar, S. Dhilip, Vikram Rana, Nandini Sreeanand, T. S. Mamatha, P. Sandhya, H. N. Nagaraja, Varun, Md. Irshad, Harikrishna Sahoo, and many members of MES have made major contributions to all the development work described above.]

Fabrication of X-ray concentrators/Optics

During 2018-19, Vikram Rana has initiated experimental activities for fabrication of X-ray concentrators/Optics. For this part of the research work a dedicated brand-new clean-room facility of 10,000 class has been constructed. Along with Biswajit Paul, he has submitted two proposals to ISRO to support future X-ray instrument development beyond POLIX for next X-ray astronomy mission where RRI will play a key role. In order to demonstrate the feasibility of the hard X-ray optics development, they have designed and fabricated automated epoxy dispensing experimental set-up to use for precisely stacking thin glass mirrors (0.3 mm thick) for the hard X-ray telescope. This will be used to establish the X-ray mirror stacking technique using epoxy and precisely machined spacers (2 x 2 x 200 mm). On successful demonstration of this technique, it will be extended to full scale hard X-ray optics assembly at RRI.
[Vikram Rana and Biswajit Paul]

Design and development of a very low radio frequency antenna

With a view to assess transparency of the ionosphere, which might vary significantly depending on the Solar cycle, and to attempt to observe the radio sky in the relatively unexplored window of very low frequencies, design and development of a very low radio frequency antenna was undertaken during the past year by Avinash Deshpande and Pavan Uttarkar. The design of the antenna is completed, and after its fabrication, it will be used (with a suitable analog receiver, along with the required back-end signal processing units, using available modules), to conduct the study in the frequency range 5-20 MHz.
[Pavan Uttarkar (SIT, Tumkur) and Avinash Deshpande]

Indian SWAN

The Indian SWAN demonstrator system of 7-tiles located at the Gauribidanur Field Station was reconfigured for suitability of relocation, incorporating separate beamformer supply and control hardware/software, as well as GPS-disciplined Rubidium frequency standard. Students were encouraged and trained in developing 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. At present, nineteen teams of students across India are participating in the SWAN Imaging Challenge 2019.
[Avinash Deshpande, C. Vinutha, K. B. Raghavendra, H. A. Aswathappa, P. Sasikumar, and other colleagues from the EEG and workshop, and of course, several student participants in SWAN, from the various institutes across India.]

Detection of redshifted 21-cm global signal from cosmic dawn and epoch of reionisation (CD/EoR)

The cosmic dawn and epoch of reionisation remains one of the least understood periods in cosmology, due to lack of observational constraints. One of the most powerful probes to study these epochs is the 21-cm signal (corresponding to a frequency of 1420MHz) arising from spin-flip transition of neutral hydrogen. The sky-averaged or global component of the 21-cm signal is a very powerful probe to study these epochs. This signal would get redshifted to lower frequencies due to cosmological expansion and is expected to be seen as distortions to the cosmic microwave background (CMB) at frequencies between 40-200 MHz. 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.

During the past year, the CMB DISTORTIONS group at RRI has concentrated on commissioning and deployment of SARAS-3 system, which is an experiment to detect the global 21-cm signal. The design of the modified system was carried out in the previous year and the major development during this year was deployment of the system at relatively radio quiet sites at Timbaktu collective in Andhra Pradesh and Hanle in Ladakh. Analysis of data has shown that the electromagnetic coupling of the antenna to ground introduces non-smooth structures into the measured spectra. This coupling strongly depends on the ground conditions and has a twofold effect. First is the modification of system transfer function and the second is the introduction of an additive component in the spectra. Efforts are ongoing to understand this effect and mitigate the issues arising from it. Moreover, to measure the antenna reflection coefficient and thereby the transmission efficiency to high accuracies, the measurement systems are getting improved. As a result of these efforts, the systematics in transmission efficiency measurements have been brought down to the range of 10^{-5}.

Besides the ground based EoR experiment, Mayuri S. Rao, Saurabh Singh and Jishnu Nambissan, have proposed a space based EoR experiment named PRATUSH (Probing ReionizATion of the Universe using Signal from Hydrogen). PRATUSH is a wide band radio spectrometer, proposed to be put in a circumlunar orbit to mitigate the effects of Earth bound RFI, ionosphere and antenna coupling to the ground. This proposal has been submitted to ISRO and seed funding has been sanctioned for pre-project development.

[Ravi Subrahmanyan, Udaya Shankar N, Saurabh Singh, Mayuri S. Rao, Jishnu Nambissan, B. S. Girish, A. Raghunathan, Somashekar R. and Srivani K. S.]

Saurabh Singh and Ravi Subrahmanyan re-analyzed and provided an alternate explanation for the EDGES measurement of the long wavelength radio sky spectrum. The EDGES group had claimed detection of redshifted 21-cm signal from Cosmic Dawn that was at least a factor of two larger than standard theoretical predictions and had features that required evoking exotic physics to explain them. Using realistic model for foregrounds, the RRI members showed that the data could be equally well explained by presence of an unmodeled, plausible systematic that had escaped their calibrations. In such a case, the data was shown to be consistent with a class of 21-cm signals predicted assuming standard cosmology, without any exotic physics. This work has been accepted for publication in The Astrophysical Journal.
[Saurabh Singh and Ravi Subrahmanyan]

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. 1). This optics demonstrates that one can trade instantaneous sensitivity with instantaneous field-of -view, while preserving the antenna throughput. This optics involves cylindrical primary that promise economy.

During the past year Ramesh Balasubrahmanyam, Sandeep H, Avinash Kotla, Sandeep K, Mohit Sinha, Kamesh, Kuldeep Singh and Charles Paul worked on this and have completed the following:

- Joint parts were made of stainless steel boxes and shoes. They have been made from SS sheets using laser cutting, CNC bending, spot welding and sheet metal work and processes. All parts needed for two side sections have been readied. They are now in the process of getting similar joint parts made for the mid- and end-sections.
- Aluminum tubes of required dimensions have been procured and sized. In particular, this involved angle cutting, which has been accomplished to a fair degree of accuracy.
- Method to make economical light- weight panels to an accuracy better than 1 mm rms has been evolved and prototype cylindrical panels have been made (Figure 5). A special purpose machine has been built to cut the cylindrical profiles on the backup. The panels are stiff and sturdy though they weigh only about 7 kg/ m^2 .

Aluminum sheets required for making the panels have recently been procured. All panels will be made once the measurement system is ready.

- A high precision laser sensor has been procured. A CMM using it is under construction. Once it is completed, the panels will be measured accurately and certified.
- Plummer blocks and bearings have been procured. Shaft and shaft joint parts are being made. Assembly of a test side section with plastic tubes has been completed. Once the shaft parts are ready, assembly of the two side sections with Aluminum tubes will be undertaken.
- Antenna base civil structure has been designed and is being built at the field station.
- A new gear system has been designed. One version of it with a belt drive has been implemented in the Supernova Search Engine and tested. This drive works well as expected but has a bit of backlash. A plastic prototype of the full system avoiding the belt is being made for testing. Once its performance is assessed, two such systems will be made for use with ELI.

To demonstrate the working of ELI, a two channel receiver is 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. 5 (Left) A CAD model view of the entire telescope structure, with its base and the mirrors set on it. (Right) A photo of a prototype cylindrical panel for ELI of size 1.2m x lm.

[Ramesh Balasubrahmanyam, Sandeep H, Avinash Kotla, Sandeep K, Mohit Sinha, Kamesh, Kuldeep Singh and Charles Paul]

Supernova Search Engine

Lekshmi Nair and Ramesh Balasubrahmanyam are building a dedicated radio supernova (SN) search engine. A typical SN exploding in our Galaxy at 30 kpc from us will be more than 100 Jy strong at its peak. At 11 GHz, a 120 cm dish antenna with a 150 K T sys receiver for 8 min of overall integration time (time for source to transit across the beam) and 0.4 GHz bandwidth will achieve 10 Jy 3.51T sensitivity, adequate for this purpose. Therefore, they are deploying a dedicated radio "Super-nova Search Engine (SnSE)".

The SnSE has four subsystems: (a) an absorber chopper; (b) 1.2m dish with its commercial low-noise block converter (LNBC) operating at 12 GHz; (c) a triplexer-cum-detector module with its digitizer; (d) software to position the antenna, acquire and store data and a GUI to display essential information.

SnSE uses a home-made optical encoder (0.5° precision), DC motors driving a new gear system and a home-made compact IF card. Other components of the system are commercial: an LNBC, Arduino board and a Raspberry Pi-2 board.

The receiver has been tested and works fine on the field (Figure. 6, Left panel). Scan of Sun as it transited through the beam recorded with the receiver is shown in Figure. 6 (Right panel). The feedback had some issues that have now been sorted out and the control is working fine. The telescope EW alignment has been done and the system is being currently painted. The receiver system is being put in a more compact box amenable for weather proofing. Soon, they hope to carry out the final tests and commission the system.

Both ELI and SnSE are transit instruments. Therefore, SnSE also serves as a test bed to develop software and hardware approaches that will benefit ELI. For example, the telescope positioning code developed for SnSE is readily usable for ELI, with an 8 times more precision position feedback. As mentioned earlier, they tested a modified version of the new drive system concept on SnSE and found that it works well. To change the position by 0.5°, the drive takes ~2s, and consumes only 0.3W. The receiver system too consumes 1. 5W. Such a low power system should run for long without trouble in the hot environs at Gauribidanur.

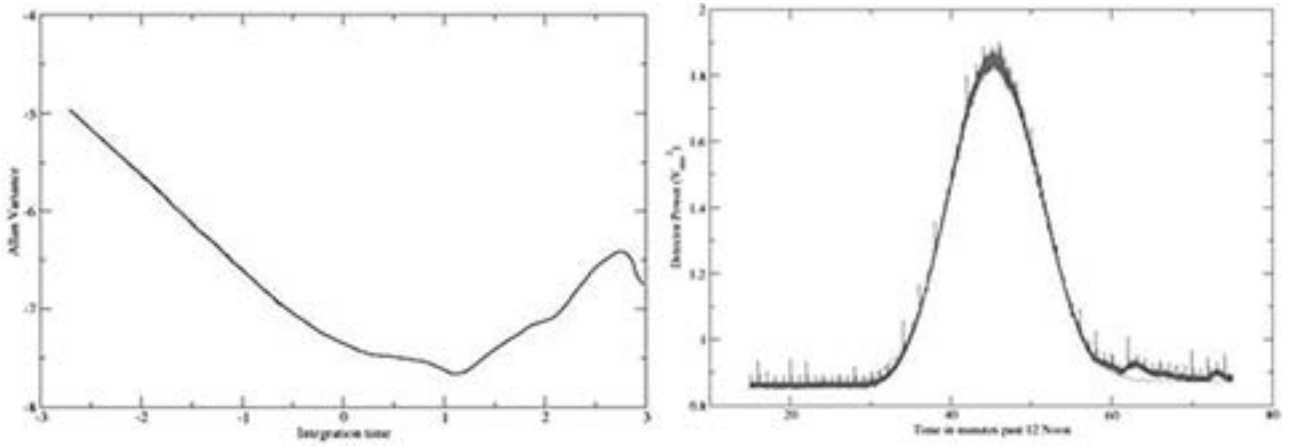


Figure 6. (Left) Allan variance test of the receiver chain. The receiver is stable to 0.3s. Simple 3 Hz load chopping would extend the integration time beyond 0.3s. (Right) A transit scan of Sun.
[Lekshmi Nair and Ramesh Balasubrahmanyam]

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.

Iridium Satellite Signals: A Case Study in Interference Characterization and Mitigation for Radio Astronomy Observations

During 2018-19, Avinash Deshpande and collaborator B M Lewis compared several post-detection approaches to the mitigation of radio-frequency interference (RFI) by applying them to the strong RFI from the Iridium satellites. These provided estimates for the desired signal in the presence of RFI, by exploiting distinguishing characteristics of the RFI, such as its polarization, statistics, and periodicity. Their data are dynamic spectra with full Stokes parameters and 1ms time resolution. Moreover, since most man-made RFI is strongly polarized, they used the data to compare its unpolarized component with its Stokes Interference. This approach on its own reduces the RFI intensity by many tens of dBs. A comprehensive approach that also recognizes non-Gaussian statistics, and the time and frequency structure inherent in the RFI, permits exceedingly effective post-detection excision provided full Stokes intensity data are available.
[Avinash Deshpande and B M Lewis (NAIC, Arecibo Observatory, USA)]

Global 21-cm signal detection

During the past year, Jishnu Nambissan along with N Udaya Shankar and Saurabh Singh has investigated various data analysis techniques to extract the global 21-cm from data. The commonly used methods involve polynomial fitting of some kind to the sky averaged spectrum (mean spectrum) to remove foregrounds. His research in this area was to explore the temporal information contained in the data collected over several hours to understand the foregrounds and remove them. The motivation behind this approach is that the foregrounds have spatial structure but a global signal, by its very definition, does not have any

such structure. This spatial structure imprints temporally varying foreground information in the measured spectra. These foreground modes can be found by performing a singular value decomposition of the spectral data. These modes can then be subtracted from the mean spectrum to detect the 21-cm signal. He carried out simulations using mock foregrounds and studied the signal loss encountered. Effects of noise on signal detection were also studied.
[Jishnu Nambissan, N Udaya Shankar and Saurabh Singh]

Analysis of MWA drift scan data for detecting EoR

One of the main stumbling block in the detection of fluctuating component of the redshifted HI signal from EoR is the changing systematics, e.g. bandpass, primary beam, etc., during the observational run. In a drift scan, one expects the system to be stable as no electronic delays are introduced for telescopes such as MWA during a run. In an earlier publication, Akash Patwa, K. S. Dwarakanath and Shiv Sethi had shown that drift scans of short periods (a few hours) might allow us to get comparable signal-to-noise as compared to tracking observations. During 2018-19 they have expanded their proposed method to delay space and also take into account the w-term and apply it to MWA phase I and II data. They have shown that the system remains fairly stable for nearly 5 hours of run by comparing the data power spectrum with noise simulations (Figure 7). Further, they have also computed, both analytically and numerically, the expected behaviour of point-source and diffuse foregrounds during a drift scan and have shown that point-source foregrounds are expected to decorrelate at a faster rate as compared to the HI signal. They also find this behaviour in the data, thus giving them another method to partially mitigate foregrounds. In the future, they aim to further analyse 50 hrs of MWA Phase II data.

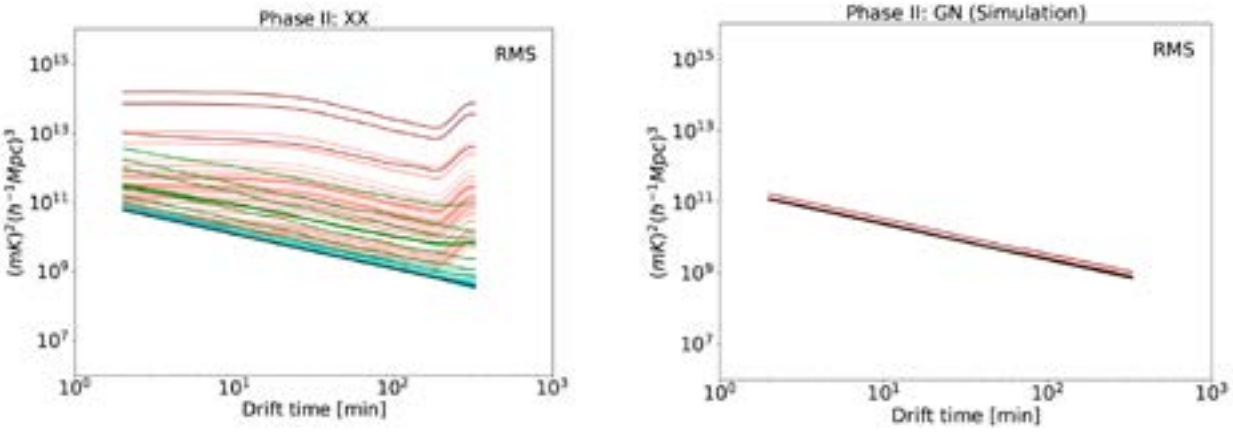
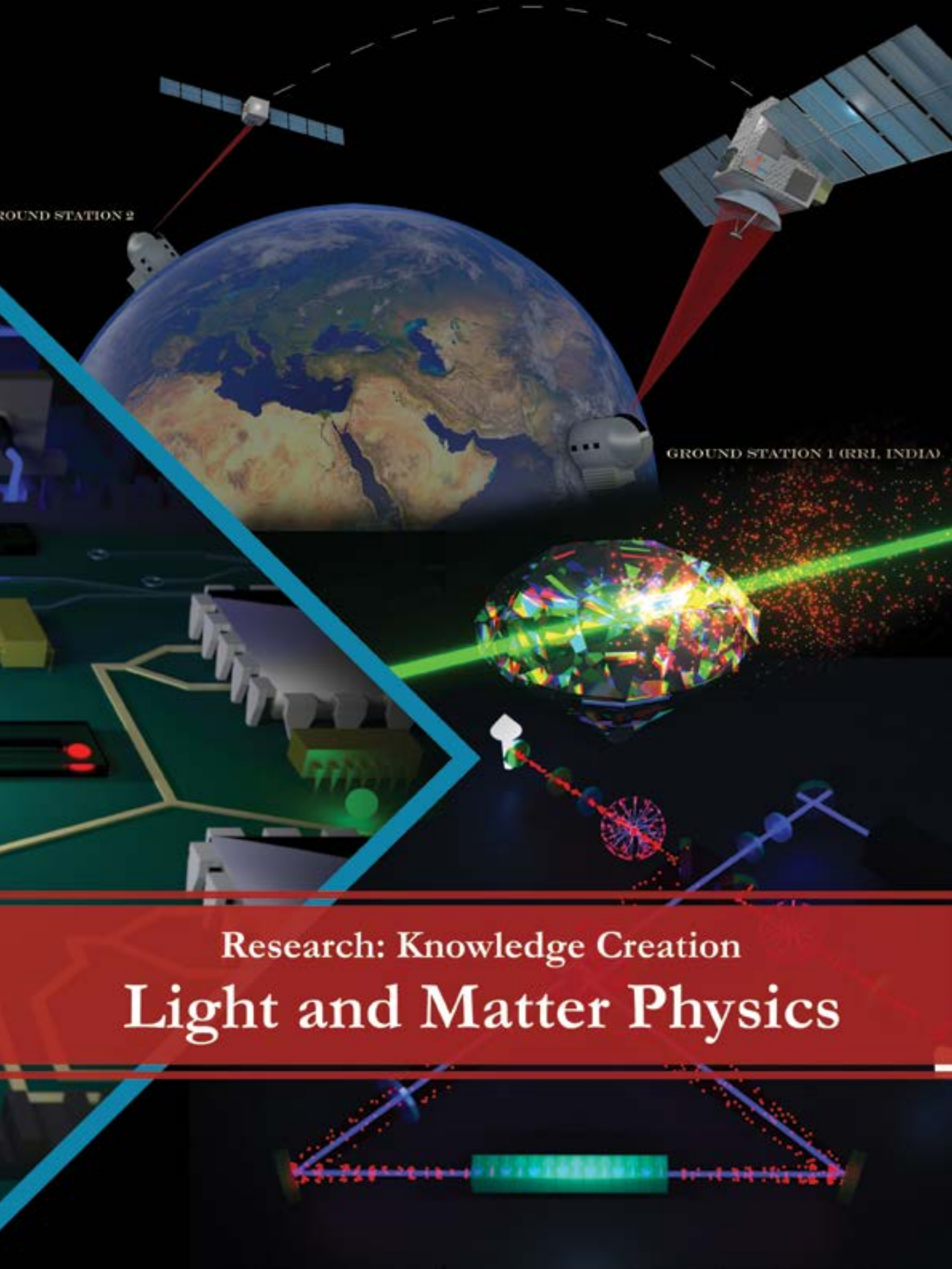


Figure 7. The plots show the RMS of mean power spectra as function of drift time. The two panels represent the data and Gaussian noise RMS (Tsys = 400 K for the simulated data). The 129 curves correspond to different values of the delay parameters τ. Curves are colour-coded keeping in view the expected 2D HI power spectrum of MWA data. Red and orange curves represent the wedge and MWA-specific bright horizontal bands, respectively. Yellow curves are two modes on either sides of horizontal bands. 'Clean' modes between the wedge and first horizontal band (orange and yellow) are shown in pink while those between the first and the second horizontal bands are shown in green. Rest of the 'clean' modes in the EoR window are equally divided in two colours; first half in sky-blue and second half in blue (largest τ values). The white curve in the data RMS is proportional to T^2/t which allows us to estimate Tsys .
[Akash Patwa, K S Dwarakanath and Shiv Sethi]



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 2018-19

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.

Cavity QED related experiments

Detection of ultracold molecules using an optical cavity

During the past year, Rahul Sawant and Sadiq Rangwala along with collaborator Olivier Dulieu theoretically studied, non-destructive detection of ultracold molecules using a Fabry-Pérot cavity. Specifically, they considered vacuum Rabi splitting and have demonstrated the use of collective strong coupling for detection of molecules with many participating energy levels. Electromagnetically induced transparency and transient response of light for the molecules interacting with a Fabry-Pérot cavity mode as a means for non-destructive detection was considered. Through this study, they identified the parameters required for the detection of molecules in the cavity using electromagnetically induced transparency and the theoretical analysis for these processes was parametrized with realistic values of both the molecule and the cavity. For each process, the state occupancy of the molecules interacting with the cavity was quantified and the extent to which the population does not change during a detection cycle was determined. This work has now been published in Physical Review A (Phys. Rev. A 97, 063405).
[Rahul Sawant, Olivier Dulieu (Laboratoire Amie Cotton, France), and S. A. Rangwala]

Measuring spatially extended density profiles using atom-cavity collective strong coupling to higher-order modes

The collective strong coupling of rubidium atoms in a magneto-optical trap (MOT) to the Laguerre-Gaussian (LG) modes of a Fabry-Pérot cavity was investigated by M. Niranjan, Sourav Dutta, Tridib Ray, and S. A. Rangwala. Bright and dark ^{85}Rb MOT atoms were prepared at the geometric center of the cavity, and the vacuum Rabi splitting (VRS) of the collectively coupled atom-cavity system was measured for LG_{l0} (l=0,1,2,3) modes. The atom number coupled to the cavity mode depends on the overlap of the atomic density distribution and the specific spatial mode function, which was reflected in the measured VRS spectrum. The known mode function and the measured VRS can then be used to test whether the atomic density distribution in the experiment is Gaussian or uniform. A simple theoretical model for this process was provided, and the experimental measurements were found to be in close agreement with the model. This work has now been published (Phys. Rev. A 99, 033617).
[M. Niranjan, Sourav Dutta, Tridib Ray, and S. A. 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's 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. This 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.

The experiment consists of laser cooling and trapping

of neutral Sodium (Na) and Potassium (K) atoms simultaneously and evaporatively cooling a large number of Na and K atoms into quantum degeneracy. Quantum degenerate mixture of Na and K atoms will be trapped in an external periodic potential created by interference pattern of the trapping laser beams. This 'artificial crystal of light' or 'optical lattice' will mimic the condensed matter systems with atoms playing the role of electrons and 'optical lattices' playing the role of the ionic crystals. Weakly bound, hetero-nuclear NaK molecules will then be created near 'Feshbach resonance' by applying external DC magnetic field. These weakly bound NaK molecules will be transferred to the ro-vibrational ground state of the singlet molecular potential of NaK via a two photon STImulated Raman Adiabatic Passage (STIRAP).

During the past year, Sagar Sutradhar, Subhajit Bhar, Maheswar Swar, Sanjukta Roy and Saptarishi Chaudhuri have focused on further developing the ultra-high vacuum and laser systems.

The Ultra-High Vacuum system:

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. Atoms from the sources will be captured in a dual-species magneto optical trap (MOT) simultaneously. The goal of the design is to capture a very large number of atoms of each species in the MOT simultaneously. Afterwards, the MOT magnetic field will be ramped up to hold the atoms in a quadrupole magnetic trap. A magnetic transport stage has been designed to simultaneously transport the trapped atoms magnetically over 60 centimetres to a connected glass vacuum cell with large optical access and ultra-high vacuum. The schematic diagram of the vacuum system is shown in Figure 1. Most of the vacuum components are either purchased or machined in RRI mechanical workshop. Ultra-high vacuum glass cells are designed in-house and are being manufactured by an external vendor.

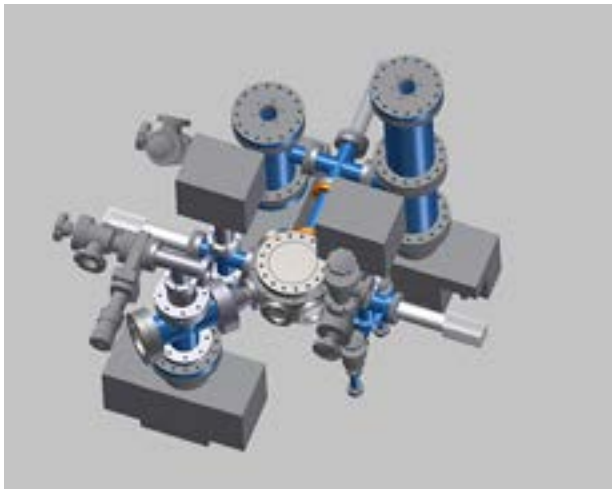


Figure 1. Schematic of the experimental set-up designed and being implemented at RRI. K and Na atoms will be collected into a dual species magneto optical trap (MOT) from two 2D-MOT sources, respectively. Thereafter, they will be magnetically transported to a vacuum cell with high optical access where the double degenerate cloud will be prepared and subsequently the molecules at ultra-low temperature will be formed.

The Laser systems:

The laser cooling transition wavelength for neutral Sodium atoms is 589 nm. A laser system whose components were purchased from Toptica Photonics GmBH has been installed. The laser system consists of an external cavity diode laser operating at the wavelength of 1188 nm. The 100 mW output of the diode laser was injected into a Tapered Amplifier which produces 8 Watts of single mode laser light at 1188 nm. This light was then injected into a bow-tie shaped cavity with a doubling crystal to produce 1.4 Watts of laser light via Second Harmonic Generation (SHG) at the desired wavelength of 589 nm. A photograph of the installed TA-SHG laser system for laser cooling of Sodium atoms is shown in Figure 2.

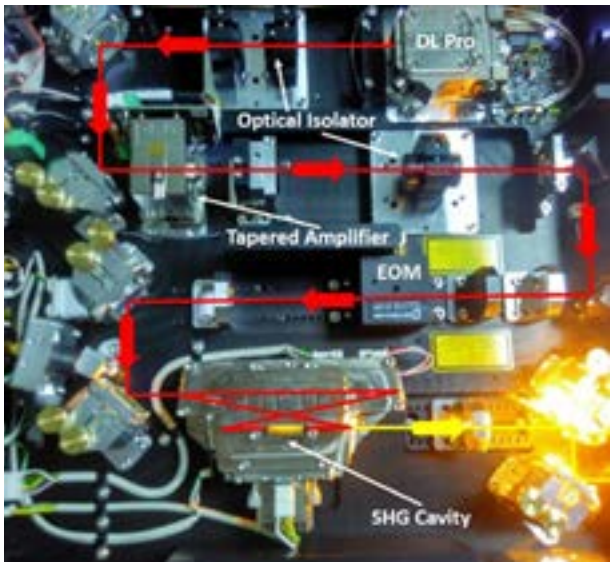


Figure 2. A photograph of the laser system installed in the laboratory to cool neutral Sodium atoms. The main components of the laser system are indicated in the figure and the path of the laser light is shown using red arrows overlaying the photograph.

The bow-tie cavity was stabilized by giving a feedback voltage to a piezo-electric transducer attached to one of the mirrors of the cavity after generating a dispersive signal from cavity transmission spectrum through Pound-Drever-Hall (PDH) technique. The phase of the laser light was modulated using an Electro Optic Modulator (EOM). The cavity transmission signal and the PDH signal is shown in Figure 3.

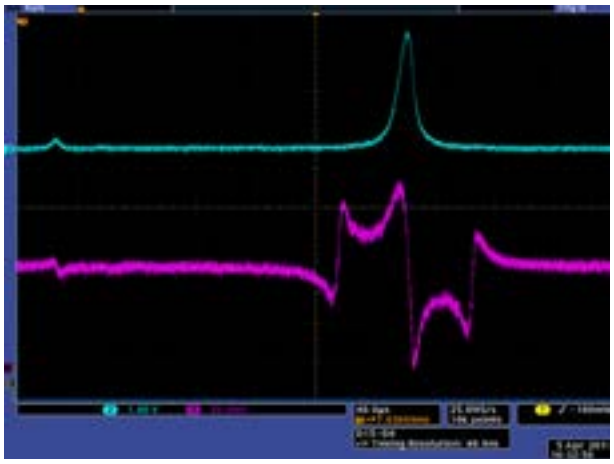


Figure 3. Oscilloscope trace of the cavity transmission signal (blue) and dispersive signal (pink) used to lock the second harmonic generation cavity.

The cooling laser was frequency stabilized with respect to the saturation absorption spectra obtained in the laboratory. A typical Sodium saturation absorption spectrum is shown in Figure 4. A single laser source is being used to generate the cooling and repump light for laser cooling and trapping of Sodium atoms. Since the hyperfine separation of F = 1 and F = 2 states for Sodium is 1713 MHz, an Electro Optic Modulator (EOM) has been installed to generate frequency side bands separated by 1713 MHz to produce both cooling and repump laser light from the same laser.

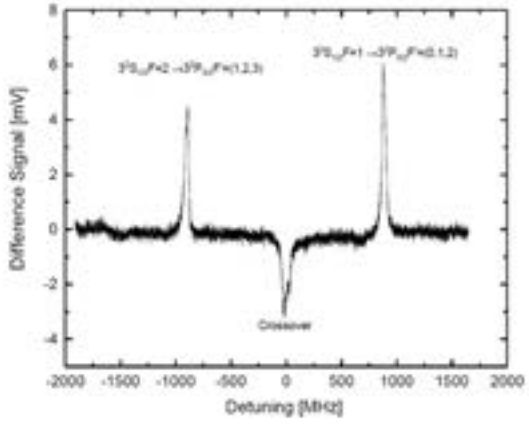


Figure 4. A typical saturation absorption signal obtained from the Sodium vapor in the laboratory.

The laser light for the laser cooling of Potassium atoms were generated from an external cavity diode laser (ECDL) with centre wavelength 767 nm (The D2 transition in potassium). The output of the laser was amplified using a tapered amplifier to produce a total laser power of 1.8 Watts. In case of potassium, two separate ECDLs were used to generate lasers tuned to cooling and repumping transitions. The laser frequency was stabilized using saturation absorption spectra. A typical saturation absorption spectra of Potassium atoms recorded in the laboratory is shown in Figure 5.

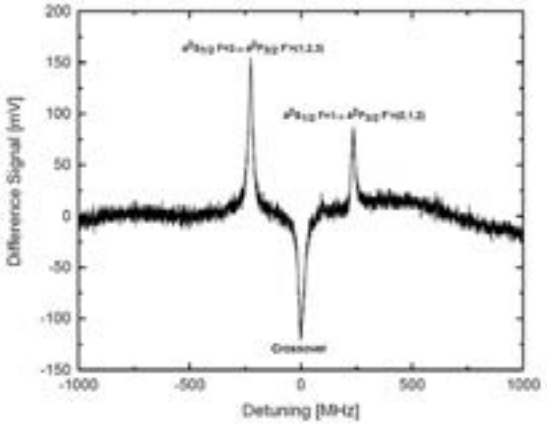


Figure 5. A typical saturation absorption spectrum for neutral Potassium atoms obtained in the laboratory. This signal is used to frequency stabilize the cooling and the repump lasers for the experiments.

Laser light used for cooling, repumping, spin polarizing and imaging were derived from the laser systems and appropriately frequency controlled using acousto-Optic Modulators (AOMs) and transported from the laser table to the main experiment table via single mode, polarization maintaining optical fibers. A photograph of the laser table with Lasers AOMs, fibers, all the optics and saturation absorption set-ups are shown in Figure 6.

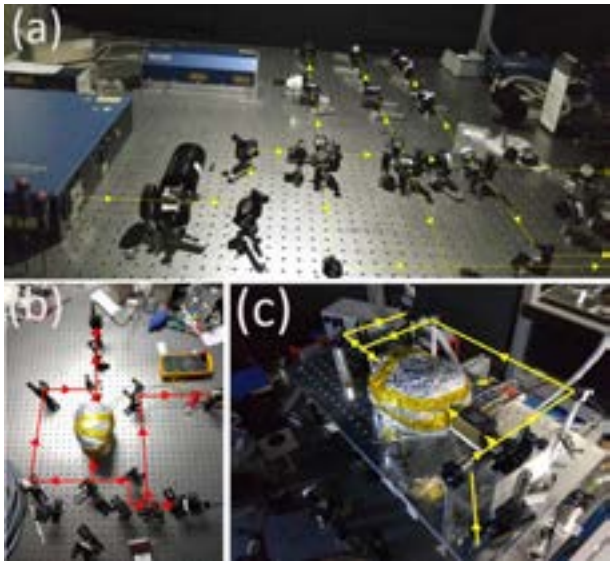


Figure 6. (a) Laser table set-up for the experiment. (b) Potassium saturation absorption spectroscopy set-up. (c) Sodium saturation absorption spectroscopy setup.

After trapping the atoms in three-dimensional magneto optical trap (MOT) they plan to transfer the cold atoms

into quadrupole magnetic trap and transport the entire cold atom cloud to a connected vacuum glass cell for further stages of the experiment. The strategy for transporting the atoms is by shifting the centre of the quadrupole field as a function of time. It was decided to vary the dc current in overlapping magnetic coils rather than physically moving the coils in order to minimize the mechanical instability. In this regard, a comprehensive computer simulation for designing the magnetic field producing coils and temporal variation of the currents in the overlapping coils have been completed. This simulation allows for designing the power supplies for the magnetic transport. All the magnetic field producing coils required for the experiment were designed and made in-house at RRI. Since the required currents are close to 200 ampere an IGBT based high current, fast (switching time of around 20 micro-second) switching circuit was developed and installed in the laboratory.
[Sagar Sutradhar, Subhajit Bhar, Maheswar Swar, Sanjukta Roy and Saptarishi Chaudhuri]

Spin correlations in cold atoms

During the past year, experiments by Saptarishi Chaudhuri has been towards trapping and cooling ^{87}Rb atoms inside a vacuum chamber by means of magneto-optical trap (MOT). In the MOT, three circularly polarized laser beams along three orthogonal directions (x, y and z) were overlapped at the position of the magnetic field center. The laser beams (MOT beams) were retro-reflected back using mirrors. Two magnetic coils in anti-Helmholtz configuration were used to produce a gradient magnetic field inside the vacuum chamber. Scattering between atoms and near resonant MOT beams reduces the velocity of the atoms due to the Doppler effect, and the atoms get captured at the center of the magnetic field. The cooling laser light beams ~12 MHz away in red detuned side from F = 2 → F 0 = 3 line of D2 transition (~780 nm). In presence of cooling and repumping beams (with correct polarization and detuning) and magnetic field gradient, the atoms start to load in the MOT.

The atom numbers in the MOT are measured using in-situ fluorescence and absorption imaging techniques respectively. The temperature of the trapped atomic cloud has been measured using absorption imaging in the time-of-flight (TOF) mode. In the optimized parameters of the MOT beams and magnetic field gradient, the details of the MOT cloud are: (a) Size (Gaussian $1/e^2$ diameter) ~1 mm, (b) Atom number ~10^7, (c) Temperature ~140 μK. The density of cold atoms in the MOT is order of ~10^{11}/cm^3.

The schematic diagram for detecting the spin correlation (SN) signal from cold atomic cloud is shown in Figure 7. First ^{87}Rb atoms are captured in the MOT. Then the cold atomic cloud is coherently driven using a pair of Raman beams. The Raman transitions between different magnetic sub-levels are thereafter detected using the spin-correlation spectroscopy techniques previously developed in the Quantum Mixtures laboratory at RRI.

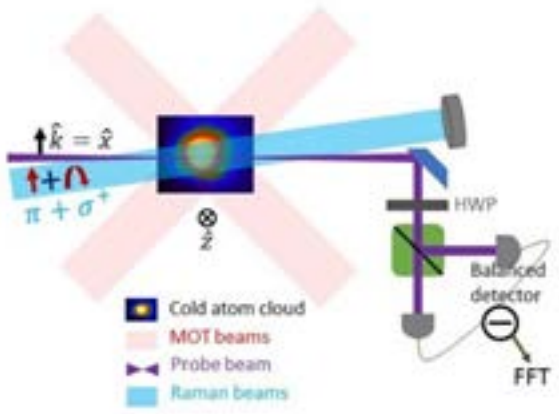


Figure 7. Schematic of in-situ spin correlations measurement using cold atoms. This cloud has been coherently driven by Raman beams during the experiment. A linearly polarized and far-detuned probe beam acquire the SN signal from in-situ cold atomic cloud.

A typical spin correlation signal obtained in the laboratory from the cold atoms is shown in Figure 8. As the Raman detuning comes into resonance with Larmour frequency there is a strong enhancement of the spin correlation signal.

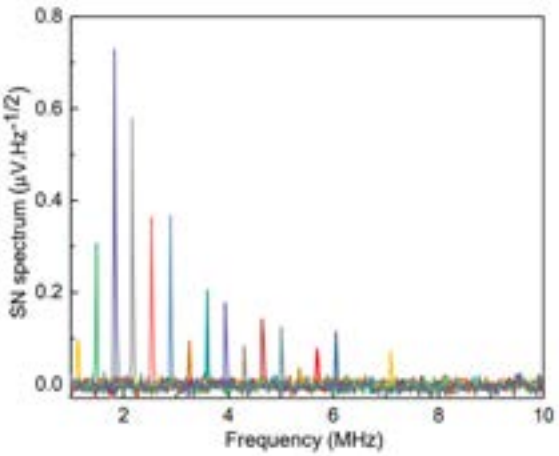


Figure 8. Spin correlation signal from cold atoms driven by a pair of Raman beams. The spin correlation spectrum is plotted against Raman detuning in the above figure.

These measurements indicate the ability to detect the small spin-spin correlation signal in the cold atomic systems with good signal to noise ratio. Since the cold atoms offer unprecedented control over both external and internal degrees of freedom, manipulating spin states and using them for coherent control is far easier compared to atomic vapor. A non- perturbative detection of spin state

populations as demonstrated by above measurements will lead to further understanding of magnetization fluctuations at ultra-low temperature and will reveal several features of quantum nature of the origin of magnetism apart from obvious applications in quantum communication and quantum memory.
[Saptarishi Chaudhuri]

Few-atom, few-photon systems

This project investigates, primarily through experiments, the interaction between single quanta of matter (atom) and single quanta of energy (photon). Isolating and holding single quanta, either of matter, or of energy, is a challenge. In the case of atoms, it requires cooling of atoms close to absolute zero temperature, and holding them trapped using specially designed traps that employ light fields, in ultrahigh vacuum containers. Detection of single photons requires ultra-sensitive detectors, fast counting techniques and handling of voluminous data very rapidly. Complex as they may be, investigations of the interactions close to the single quantum limit will not only enable one to learn of the fundamental processes in nature, it will also provide mechanisms for many front-line applications like the creation of quantum logic gates, quantum memory, and photons-on-demand sources. Sanjukta Roy, Shilpa and Hema Ramachandran are interested, in particular, in quantum logic gates where atoms constitute the qubits. The internal states of the atoms and their interactions can be controlled by light, giving rise to several protocols for implementing quantum logic gates. One such scheme involves dipole-dipole interaction between neighbouring atoms. As atoms that are excited to very high principal quantum numbers, the so-called Rydberg atoms, can possess high dipole moments, the thrust has been to excite atoms to the Rydberg state and study their interactions.

During the past year, this work has progressed with the following achievements:

- The setup to trap single atoms has been improved on several fronts. The starting point of the single atom trap was a magneto-optic trap, which cools and traps about 4000 atoms to about 100microkelvin. A tightly focused optical beam was superposed on this collection of atoms that forms a microscopic dipole trap, of size of the order of the wavelength of light. Due to the mechanism of collision blockade, this trap confines at most one atom.
    - The same optical elements that direct the dipole beam into the vacuum chamber were also used to collect the emission from the single atom and send it to the Hanbury-Brown Twiss type of setup that acts as a diagnostic for the single atom trap. The refractive indices of the optical elements differ by a slight amount at the two wavelengths used – the trapping wavelength and the emission wavelength. This normally would be inconsequential. However, at the single atom trap level, where the required focusing is diffraction limited, and atoms are confined to sub-micron traps, such differences lead to large consequences. Careful and systematic evaluation of the effects arising due to the different refractive indices were carried out, and corrections were incorporated.
    - A single atom remains trapped in a dipole trap for a certain amount of time before it is lost. Collisions with background atoms, scattering of light, and intensity fluctuations in the dipole trap laser are the dominant causes for trap-loss. Each of these have been evaluated, and parameters optimized, so that the lifetime for a single atom in their dipole trap is now estimated to be ~1 second.

- Room temperature rubidium atoms have been excited to Rydberg states via a two-photon mechanism. Atoms were excited from the ground state to the first excited state of $5P_{3/2}$ by means of a laser in the near-infrared. These atoms were then excited to Rydberg states with principal quantum number in the range of 42-50 by means of a laser in the blue region of the spectrum. This has now provided familiarity with excitation to Rydberg states which forms a crucial ingredient in some of the quantum logic protocols that they will be exploring in the future.

- A very interesting quantum-optical phenomenon is that of Electromagnetically Induced Transparency (EIT), where a normally absorbing medium is rendered transparent to a certain wavelength (probe) in the presence of light at another specific wavelength (control). This window of transparency appears as a very narrow dip in the absorption profile of the medium. Ladder-type EIT in rubidium atoms were observed, where the transitions involved are between the ground state, the first excited state, and a Rydberg state with a transparency window width of ~ 3MHz.

[Sanjukta Roy, Shilpa and Hema Ramachandran]

Precision Atom-Light Interaction and Spectroscopy

Demonstration of phase sensitive amplification (PSA) in a Delta system

For the past few years Asha K., Adwaith K V, Pradosh K N, Meena M S and Andal Narayanan along with collaborator Fabien Bretenaker have been experimentally studying an atom-light interaction scheme which involves light fields and atomic energy states interacting with each other in a cyclic and closed fashion as shown below. In their experiment the system used was specific D1 hyperfine energy levels of ^{85}Rb atoms which interacts cyclically with two optical fields (w_c and w_p) and one microwave (w_m) field.

Under specific condition of two-photon resonance, satisfied by detunings of the optical fields from their common excited state the optical beat-note becomes exactly equal to the microwave frequency and hence the system becomes sensitive to the relative phase between all the three fields.

Phase sensitivity leads to not only phase sensitive refraction and absorption properties of the bulk atomic medium but also to phase sensitive non-linear responses. Earlier the Quantum Optics lab had demonstrated the possibility of phase sensitive amplification of a signal in the optical domain.

During the past year they have completed this study where they demonstrate an amplification of probe optical field

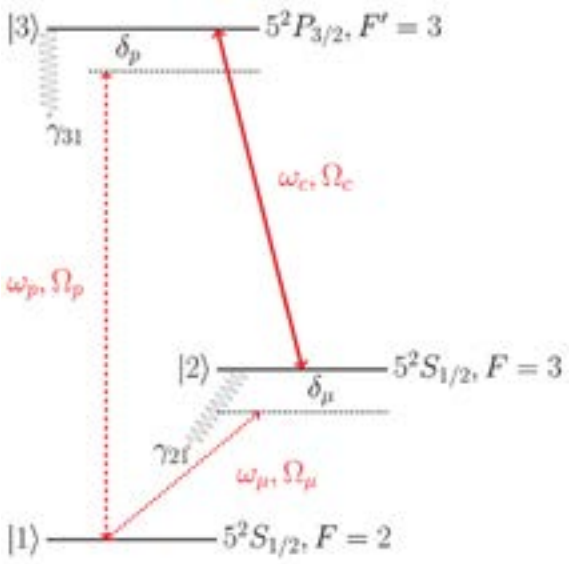


Figure 9. Shown above is the gain experienced by the probe field as a function of phase of the microwave which is also the relative phase of all the three fields

by about 7 dB which is controlled by the phase of the microwave thus demonstrating phase sensitive coherent amplification of an EM field which is controlled by another EM field which is several orders separated in its frequency. [Asha K, Adwaith K V, Pradosh K N, Meena M S, Fabien Bretenaker (Adjunct Professor, RRI and Laboratoire Amie Cotton, France) and Andal Narayanan]

Estimating the fluorescence into an optical nanofiber by performing field quadrature noise measurements.

During a sabbatical year at the University of Calgary, Andal Narayanan took part in building a cold atom vacuum setup which was subsequently used to trap Rb atoms and cool them to ultra-low temperatures of the order of few hundred microkelvin. An optical nanofibre was incorporated into the vacuum arrangement and fluorescence emitted from the cold atoms was detected. The detection of this fluorescence was done by balanced homodyne detection of the electromagnetic field which essentially measures the noise in the field. The idea behind noise measurements is that if an EM field is coupled inside the fiber it will manifest itself as increased noise in field quadratures.

During the past year, Andal Narayanan and collaborators found that the autocorrelation function of the homodyne detector's output photocurrent exhibits exponential fall-off with a decay time constant of 26.3±0.6 ns which is

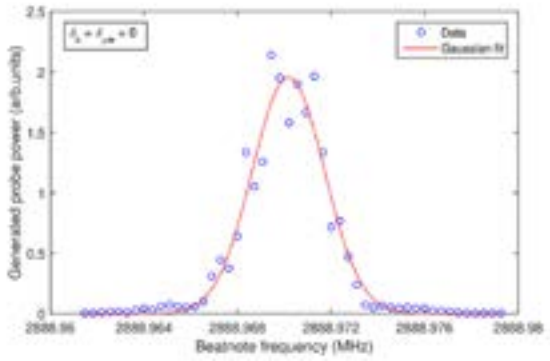


Figure 10. Spectral width of the generated probe field is shown when both the coupling and the microwave fields are at resonance with their respective transitions. The experimental points are shown as circles with a Gaussian fit shown as a continuous line. The RBW was 100 Hz for this measurement.

the expected decay time constant of the excited level responsible for the fluorescence. This work has now been published in Optics letters under the title "Measuring fluorescence into a nanofiber by observing field quadrature noise."
[Andal Narayanan and collaborators from University of Calgary: Shreyas Jalnapurkar, Paul Anderson, E. S. Moiseev, Pantita Palittapongarnpim, P. E. Barclay, and A. I. Lvovsky (Oxford University formerly at ICTS, University of Calgary, Canada)]

Spin correlations in hot and cold Rubidium atoms

Saptarishi Chaudhuri is leading a set of experiments using atomic vapours and more recently using ultra-cold atoms which investigates the spin properties of the atomic system. Saptarishi along with Maheswar Swar, Dibyendu Roy, Subhajit Bhar, Priyanka G L, Hema Ramachandran and Sanjukta Roy has experimentally explored the applications of spin noise spectroscopy (SNS) for detection of the spin properties of atomic ensembles in and out of equilibrium. Recently they published the first set of results from this experiment in Optics Express, 26, 32168 (2018) and as a book chapter in Emerging Trends in Advanced Spectroscopy, River Publisher, 2019. In SNS, a linearly polarized far-detuned probe beam on passing through an ensemble of atomic spins acquires the information of the spin correlations of the system which is extracted using its time-resolved Faraday-rotation noise. The experimental arrangement used by them shown in figure 11.

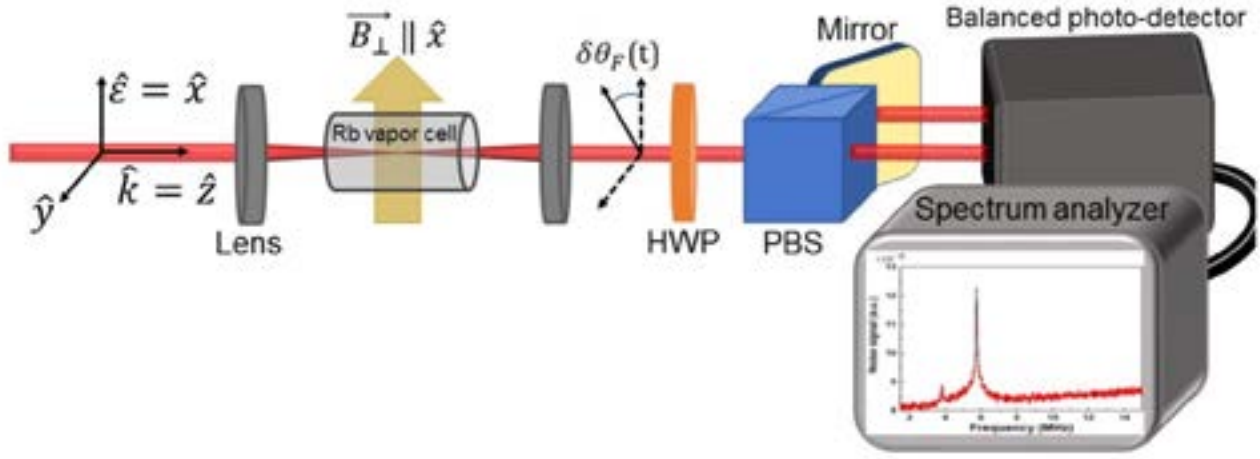


Figure 11. Schematic of the experimental set-up for measuring spin noise (SN) spectrum. A probe beam along z-direction is focused by a plano-convex lens before entering the vapor cell. The transmitted probe beam is sent through a polarimetric set-up comprising of a half-wave plate (HWP) and a polarizing beam splitter (PBS), and then it is collected by a balanced photo-detector which is connected to a spectrum analyzer. A constant magnetic field B along x-direction is applied on the atomic vapor using two magnetic coils in Helmholtz configuration.

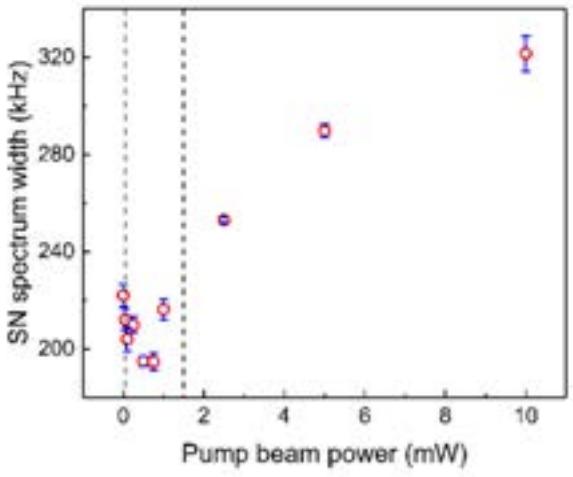


Figure 12. Reduction of the width of the spin noise signal as a function of the optical pumping beam intensity indicating the increase in spin relaxation rates.

The highlight of this research work has been the demonstration of high precision magnetometry using spin noise measurements and non-perturbative detection of atomic population in different hyperfine states. They have also obtained new experimental results of reduction of spin noise signal width as a function of the intensity of a control laser beam (Figure 12). These results imply that one could control the spin relaxation rates in atomic vapors using external electromagnetic fields. This spin-exchange relaxation free techniques have far reaching applications in quantum control in atomic systems.

[Maheswar Swar, Dibyendu Roy, Subhajit Bhar, Priyanka G L, Hema Ramachandran, Sanjukta Roy and Saptarishi Chaudhuri]

Light transport in random media

Light, that normally travels ballistically (i.e., in straight-line paths) turns diffusive when traversing a medium with randomly placed refractive-index inhomogeneities. An example of this is atmospheric fog. Light gets multiply scattered, making it difficult to view or image through such media. Several schemes for imaging through such media are known, but these either require expensive ultrashort pulsed lasers or fast electronics, or long computations. Shashank Kumar, Bapan Debnath, Shankar Dhar and Hema

Ramachandran along with collaborators have devised a technique - the quadrature lock-in detection technique – that utilises an inexpensive incoherent light source, a low-cost scientific camera, and a software developed for this purpose that enables the extraction of ballistic photons so as to form images through scattering media. This had been tested in table top experiments and had yielded good results. However, the efficacy of this technique in imaging through real fog was unknown. Experiments carried out in Uttar Pradesh, in the months of December 2018 and January 2019 wherein the object to be viewed was placed 150m away from the camera, and imaging was attempted when there was intervening fog showed that the object could be successfully imaged using the quadrature-lock-in detection technique, even when the visibility was merely 50m.

[Shashank Kumar, Bapan Debnath, Shankar Dhar, Julien Fade, Fabien Bretenaker, Hema Ramachandran. The members involved in this work are grateful to Rupamajari Ghosh, Vice Chancellor, Shiv Nadar University for providing the space and logistics for setting up of the experiment at their campus in Gautam Budh Nagar)]

Brain-Computer Interfaces

A Brain-Computer Interface (BCI) is a fascinating and powerful system that monitors the brain signals of a subject and enables the driving of devices and performing of actions, without any actual physical movement by the subject. Thus, a BCI can help a paralysed, or a physically challenged person become less dependent on others. Anubodh Yadav, Shruthi K. R., S. Sujatha and Hema Ramachandran have developed, over the last few years, a complete BCI system in-house, right from the electrodes to the bio-amplifier, the digitiser and signal processor, and finally the device driver. During the past year, the following have been achieved:

- SSVEP-based speller: Patients suffering from severe motor disabilities like stroke, locked-in syndrome, paralysis, are incapable of speech, making communication with the outside world a near-impossibility. A BCI-speller is a device that enables such persons to spell out words on a computer screen by means of certain EEG potentials that are evoked by the subject and monitored by the device. During 2018-19 a SSVEP-based speller that uses Steady-State Visually evoked potentials has been made, tested and optimized. The letters of the alphabet appear in a grid of boxes on a screen. Each element of the grid flickers on and off at a certain frequency. The subject turns his attention to the letter to be selected; a potential appears in the occipital area that oscillates at the frequency with which the letter is flickering – the steady-state visually evoked potential. A spectral analysis of the EEG reveals the letter of interest. Thus, one by one the different letters are selected to spell out the word and then the sentence. This, undoubtedly, is a time consuming process. The unique feature of the in-house developed speller is that they have significantly reduced the time taken to spell out a word, and have in fact, made it independent of the length of the word. Examining the frequency of occurrence of letters in words, it has been found that specification of 3 letters of the words greatly reduces the number possibilities of the words, enabling a rapid homing to the correct word. A 95% accuracy, and information transfer rates of 21 bits/s were obtained.

[Anubodh Yadav, Shruthi K.R., S. Sujatha and Hema Ramachandran]

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, Reji Philip and co-workers studied the nonlinear transmission of strong laser radiation (10^8 to 10^9 W/cm^2) through nanostructured and other novel materials. Moreover, laser-produced plasmas were generated on solid target surfaces using intense laser pulses (10^{14} to 10^{16} W/cm^2) and their optical and electrical properties were investigated. Another area of work was the fabrication of nanoscale patterns on solid surfaces using lasers.

[Reji Philip, Pranitha Sankar, Nancy Verma, Nithin Joy, Agnes George]

Optical power limiting by novel materials of the nano and other size domains

Optical power limiters are nonlinear optical devices designed to 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 low transmittance at high input powers. Thus, the optical limiter will be able to protect sensitive optical detectors and human eyes from damage due to accidental laser beam exposure. A practical optical limiter has to meet stringent requirements including low-intensity transparency, high-intensity opacity, broad wavelength range of operation, large dynamic range,

ultrafast temporal response and high damage threshold. Very few materials can meet all such requirements simultaneously, and therefore, the search for newer and better optical limiters is ongoing in many laboratories across the world, mostly by employing the measurement technique of open aperture Z-scan.

Open aperture Z-scan measurements in diverse materials including defect engineered $Mn_XZn_{1-X}O$ (x= 0.03, and 0.05) nanostructures [Antony et.al., *Cer. Int.* **45**, 8988 (2019)], silver added organic 2-methyl-5-nitroaniline crystals [John et.al., *Opt. Las. Tech.* **113**, 416 (2019)], discotic liquid crystals [Gowda et.al., *New J. Chem.* **42**, 19034 (2018)], lead-free ferroelectric nanostructured perovskites [Sadhu et.al., *Appl. Phys. B.* **124**, 200 (2018)], and silver-adsorbed chalcones [John et.al., *Opt. Mat.* **84**, 409 (2018)] were carried out during the past year. The effective two-photon absorption coefficient values of these materials at the wavelength of 532 nm, for 5 ns laser pulses, have been calculated from the measurements. Some of the values obtained are comparable to or better than those reported for benchmark optical limiters in literature, indicating the potential use of these materials for optical power limiting applications.
[Reji Philip, Nithin Joy, Agnes George and Sandeep Kumar]

Generation and characterization of laser-produced plasmas (LPPs)

Generation of plasma due to the interaction of an intense laser pulse with a target is a complex phenomenon. The nature of the interaction depends on laser characteristics (fluence, pulse duration, wavelength, beam quality), target composition, nature of the target surface, and the background gas in which the plasma is formed (pressure and composition). The field of laser-produced plasmas is very active due to a multitude of applications. While nanosecond LPPs are well investigated in the past, femtosecond LPPs are relatively more recent. Therefore, there is great scope for comparative studies between nanosecond and femtosecond excited LPPs.
Reji Philip and co-workers have carried out time-resolved optical emission spectroscopic studies of a picosecond laser produced Cr plasma [Rao et.al., *Phys. Plasm.* **25**, 063505,

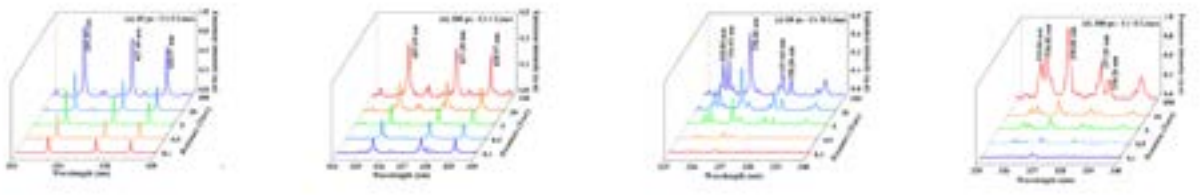


Figure 13. Evolution of Cr I and Cr II emission lines with ambient pressure for 60 ps ((a) and (c)) and 300 ps ((b) and (d)) laser pulse irradiations. Measurements were carried out using an ICCD detector, with the gate delay and gate width set at 50 ns and 200 ns respectively [From K.H. Rao et.al., Phys. Plasm. 25, 063505 (2018)].

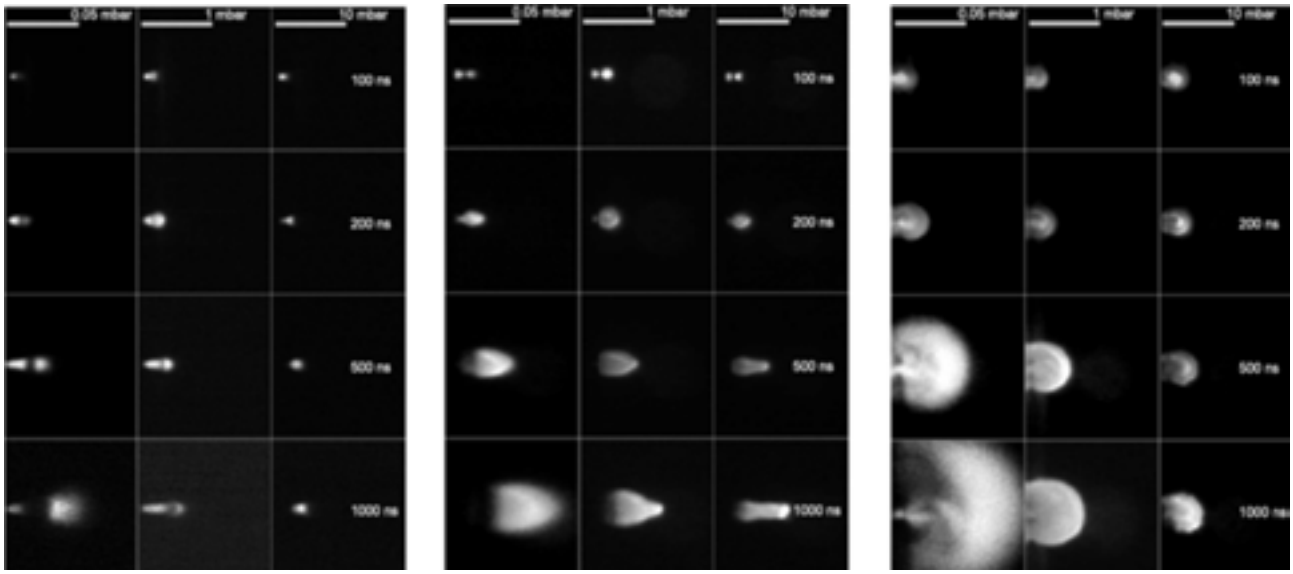


Figure 14. Temporal evolution of a rear ablated nickel plasma plume generated in a 50 nm thick Ni thin film using three different laser wavelengths and pulse widths, viz. (a) 800 nm, 100 fs; (b) 800 nm, 200 ps, and (c) 1064 nm, 10 ns. The plume expands into a nitrogen background of pressure 5×10^{-2} mbar, 1.0 mbar and 10 mbar respectively. The ICCD gate width is 50 ns, and the duration of measurement is 2 μs [from Thomas et.al., J.Phys.D.Appl.Phys. 52, 135201 (2019)].

2018], laser pulse-width dependent dynamics of LPP from a Ni thin film [Thomas et.al., *J. Phys. D: Appl. Phys.* **52**, 135201, 2019] and the effect of ambient gas pressure on nanosecond LPP from Ni thin films in a forward ablation geometry [Thomas et.al., *Phys. Plasm.* **25**, 103108, 2018]. They also investigated the effect of laser beam size on the dynamics of a femtosecond laser-produced aluminium plasma [Sankar et.al., *Phys. Plasm.* **26**, 013302, 2019].
[Reji Philip, Pranitha Sankar, Nancy Verma, K.K. Anoop (CUSAT, Cochin), J. Thomas (IPR, Ahmedabad), R.T. Sang (Griffith University, Australia)].

Surface nanostructuring using ultrafast lasers

Laser-induced periodic surface structuring (LIPSS) provides a fast and effective way to modify a material by altering its surface morphology, for tailoring its properties such as wetting, light absorption and emission, adhesion, etc. During the past decade, LIPSS has been very successful in fabricating diverse surface features, including polarization directed periodic surface structures, cone arrays, submicron spikes, and random patterns. LIPSS patterns are formed from the interference between incident laser light and surface scattered electromagnetic waves (SEWs). Most experimental studies on ultrafast laser surface structuring are based on laser irradiation at 800 nm wavelength (output of the Ti:Sapphire laser) and very few studies have used shorter wavelengths for surface patterning. Therefore, one of the current goals has been the generation of LIPSS patterns using 400 nm radiation, measurement of its modified physical properties, and comparison with LIPSS patterns produced by 800 nm irradiation.

In recent work [Anoop et.al., *Phys. Plasm.* **25**, 063304, 2018] ultrashort pulses from a Ti:sapphire laser (800 nm, 100 fs) were used to fabricate large area (5×4 mm^2) nanoscale order laser-induced periodic surface structures (LIPSSs) on a silicon (100) surface. Sample characterization led to the observation that the LIPSS patterns are strongly dependent on the laser pulse energy, state of polarization, number of shots delivered on the target and ambient pressure. The patterned silicon surface showed a substantially reduced broadband optical reflectivity in comparison to plain silicon. When characterized using laser induced breakdown spectroscopy (LIBS), enhanced optical emission and ion current were observed from the patterned surface. While plain silicon gave LIBS ionic lines only from singly ionized silicon, patterned silicon gave spectral lines emitted by doubly ionized silicon as well. Moreover, a clear enhancement was measured in both optical (50%–90%) and electrical (34%) signals from the LIBS plasma generated on the patterned surface. These results show that coupling of laser energy onto an irradiated silicon surface can be enhanced by means of LIPSS patterning. Finally, the role of laser wavelength was studied by using the second harmonic output (400 nm) for LIPSS patterning.
[Reji Philip, Nancy Verma, K.K. Anoop (CUSAT, Cochin)]

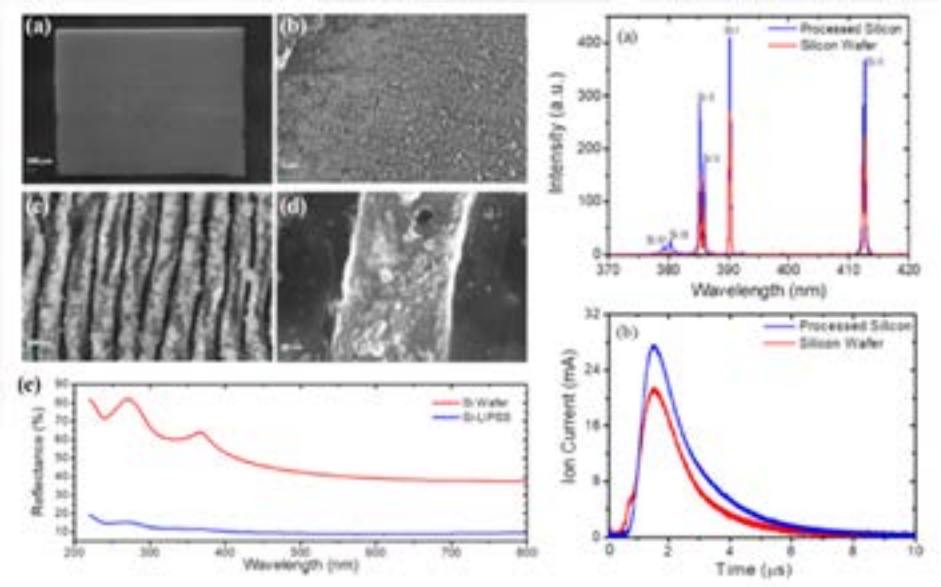


Figure 15. Left panel: (a) SEM image of a large area Si-LIPSS fabricated using 800nm, 100 fs laser pulses in atmospheric conditions. (b), (c), and (d) show zoomed views of (a). Note the different magnifications on each SEM image. (e) shows the reflection spectra measured for a plain silicon wafer and a Si-LIPSS. Reflection is found to be much less for Si-LIPSS in comparison. Right panel: (a) Relative intensity enhancement seen in (a) LIBS spectra, and (b) ion current signals, from laser produced plasma generated on the large area Si-LIPSS. Blue colour represents signals from patterned silicon while red represents signals from plain silicon wafer [from Anoop et.al., *Phys. Plasm.* **25**, 063304 (2018)].

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

Quantum Communications

In the Quantum Information and Computing lab at RRI, Kaushik Joarder, Rishab Chatterjee, Sourav Chatterjee, A. Nagalakshmi, A. Anuradha, Rakshita R.M. and Urbasi Sinha have embarked on 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.

The project started in January 2018 and the last one year has essentially seen 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 this year. They have been able to establish the B92 protocol in the lab with an average key rate of ~ 50 Kbits/second and average QBER of ~ 3.5% over a ~ 2 metre free space distance. Further optimization is underway to continue improving upon this. Details of the work on this project can be found at http://www.rri.res.in/quic/

Figure 16. A photograph from the Quantum Information and Computing lab which shows a part of the single photon source that was used to establish the B92 protocol in the lab. The source has very high singles and pair generation rates. The average Coincidence rates is 0.56 MHz while the average pair generation rate is 17.1 MHz

In addition to the establishment of the B92 protocol, the group has also established a systematic approach and implemented a rigorous approach for the simulations involved in the QKD key rate and Quantum Bit Error Rate (QBER). These novel simulations as well as experimental demonstration is being prepared as a manuscript to be submitted.

[Kaushik Joarder, Rishab Chatterjee, Sourav Chatterjee, A. Nagalakshmi, A. Anuradha, Rakshita R.M. and Urbasi Sinha]

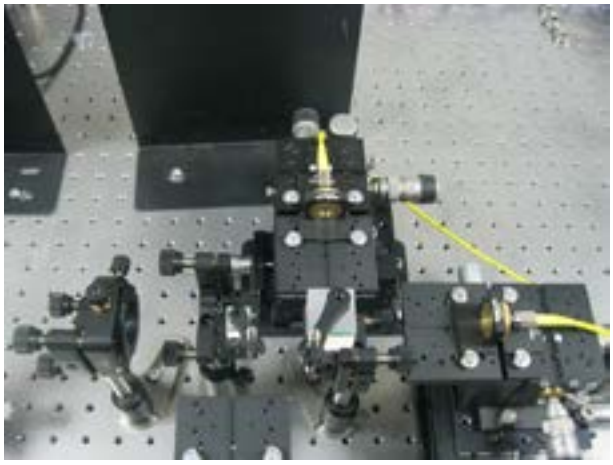


Figure 17. A part of Alice's end of the B92 protocol.

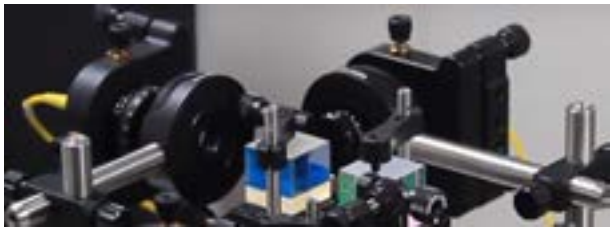


Figure 18. A part of Bob's end of the B92 protocol.

Quantum Optics

What happens when two photons are incident on the two input ports of a 50:50 beam splitter? If these photons are completely indistinguishable, they exit the beam splitter trough either one of the output ports. i.e. they both exit together through one of the available output ports. This is a classic example of a quantum optics phenomenon called photon bunching and the name of this effect is the Hong-Ou-Mandel effect after the three people who discovered this effect. The experimental measure is the photon-photon second order cross correlation function.

Given zero path difference between the two input paths, as both photons exit through one port only, the cross correlation function measures to being a zero. Thus a plot of the cross correlation between the two output ports as

a function of the path difference between the incident photons would lead to a "dip" at zero path difference. This is called the Hong-Ou-Mandel dip or the HOM dip in short. The HOM dip is a ubiquitous workhorse for quantum optics, used for measuring photon purity and distinguishability, heralding optical quantum computing gates, conceptually underpinning the complexity of the Boson sampling problem and realizing a N00N state for quantum metrology. In work completed this past year, S. Sadana, D. Ghosh, K. Joarder, A. Nagalakshmi and U. Sinha along with collaborator B. C. Sanders experimentally and theoretically addressed and resolved an important incorrect folklore concerning the Hong-Ou-Mandel dip. They addressed the fundamentally significant misconception that a 50% dip is the boundary between classical and quantum optics whereas they show experimentally and theoretically that even a 100% dip can be achieved classically; they furthermore show that the classical-quantum transition is achieved by demonstrating Complementarity, in this case being a pair of experiments with a fixed source that show a two-photon state behaves like a particle or like a wave, depending on the type of measurement. Curiously, this subtle yet important point has no experimental demonstration in literature and they are the first team to point out this misconception both in experiment and in theory.

Experiments both in the classical microwave domain and in the quantum infrared domain of the electromagnetic field showed that the microwave field demonstrates a near-100% dip despite being classical. They also showed how one can adjust the phases of input fields to manifest either particle-like or wave-like features but not both. Finally, it was shown that their infrared experiment manifests both particle-like and wave-like features with a fixed source, thus being quantum based on the Complementarity principle.

The classical experiment involves an innovative, carefully designed all electrical scheme. This innovation eliminates polarization and alignment issues leading to a clean, precise experiment beyond the capability of optical systems, which enabled tremendous accuracy and precision in demonstrating 100% TPCVD with classical fields.
This work has been reported on the arXiv (Near-100 % two-photon-like coincidence-visibility dip with classical light and the role of complementarity, arXiv: 1810.01297) and is being considered for publication in a refereed journal.

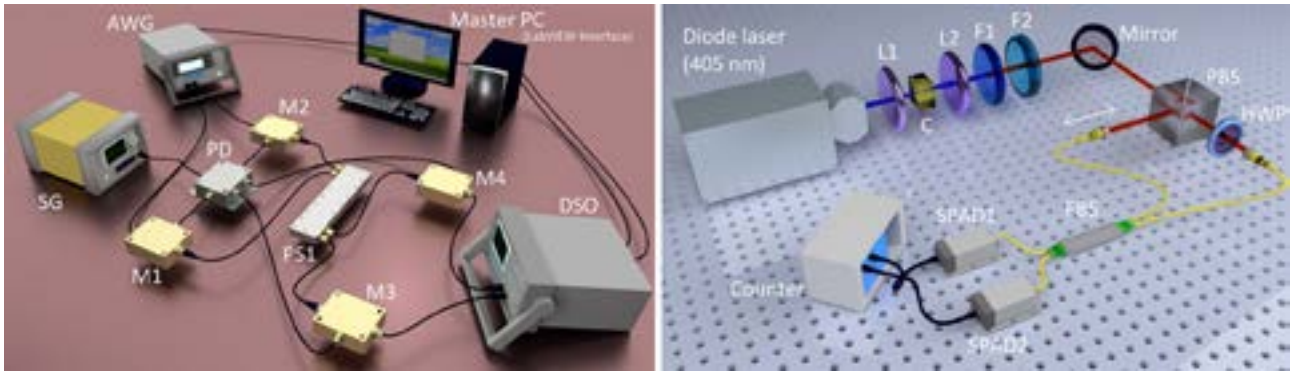


Figure 19. Schematics of the classical (left) and quantum/photon based (right) HOM experiments [arXiv: 1810.01297]

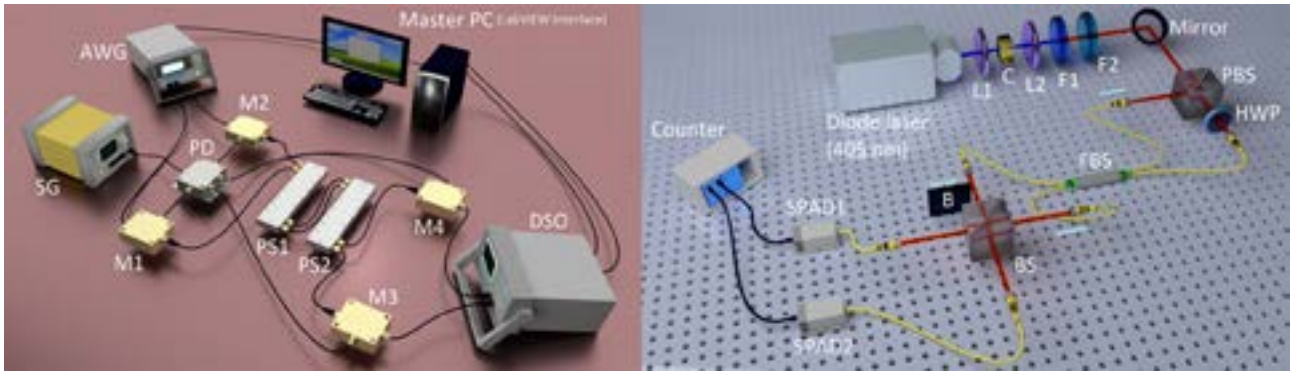


Figure 20. Schematics of the classical (left) and quantum/ photon based (right) Complementarity experiments [arXiv: 1810.01297]
[S.Sadana, D. Ghosh, K. Joarder, A. Nagalakshmi, B.C.Sanders (University of Calgary, Canada) and U.Sinha]

Fundamental Tests of Quantum Mechanics

While the Quantum Information and Computing lab focuses on cutting edge experiments which have both scientific as well as technological implications, the basic principle of the lab remains exploitation and exploration of laws of quantum mechanics. One of their thrust areas always has been towards investigation of various principles of quantum mechanics with precision experiments. This 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, Urbasi Sinha and collaborators were able to prove the existence of a correction term to the commonly naïve application of the Superposition Principle in slit based interference experiments.

The Feynman path integral formalism has long been used for calculations of probability amplitudes. Over the last few years, it has been extensively used to theoretically demonstrate that the usual application of the superposition principle in slit based interference experiments is often incorrect. This has caveat in both optics and quantum mechanics where it is often naively assumed that the boundary condition represented by slits opened individually is same as them being opened together. The correction term comes from exotic sub-leading terms in the path integral which can be described by what are popularly called non-classical paths. During 2018-19, G. Rengaraj, U. Prathwiraj, S. N. Sahoo, R. Somashekhar and U. Sinha published (New Journal of Physics, 20 063049, 2018) the first experimental measure of this correction term in the classical (microwave domain). They report an experiment where they have a controllable parameter that can be varied in its contribution such that the effect due to these non- classical paths, referred to as sub-leading paths, can be increased or diminished at will. Thus, the reality of these sub-leading paths is brought forth in a classical experiment using microwaves, thereby proving that the boundary condition effect being investigated transcends the classical-quantum divide and that the Feynman path integral formalism is an overarching framework. The first measurement of a deviation (as big as 6%) from the superposition principle in the microwave domain was measured by them using antennas as sources and detectors of the electromagnetic waves. They also show that the results can have potential applications in astronomy. The work also has a video abstract: https://www .youtube.com/watch?v=Z7efUChByH0
Report about this work is in:
https://physicsworld.com/a/exotic-non-classical-paths-affect-quantum-interference-experiment-confirms/

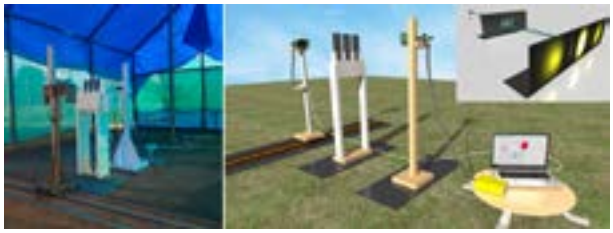


Figure 21. Figure on left shows the actual experimental set-up at the Gauribidanur observatory. Figure on right shows the schematic of the set-up [New Journal of Physics, 20 063049, 2018]

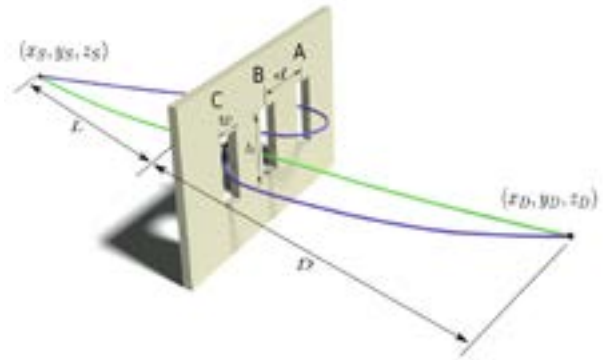


Figure 22. Pictorial representation of classical (green) and non-classical (purple) paths in the Feynman Path Integral Formalism [Physical Review Letters, 113 120406, 2014]

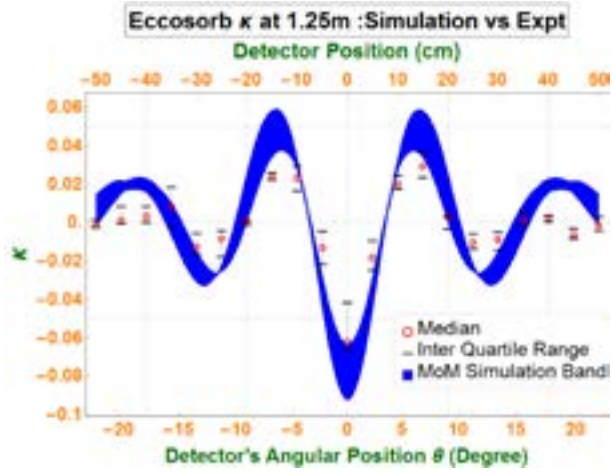


Figure 23. Representative k (normalized Sorkin parameter) as a function of detector's angular position. k is a nicely modulating function of the detector position. The non-zero k captures the correction term in the naïve application of the Superposition Principle in interference experiments. [New Journal of Physics, 20 063049, 2018]

[G.Rengaraj, U.Prathwiraj, S.N.Sahoo, R.Somashekhar and U.Sinha]

Quantum Information

In the realm of Quantum Information, this year members of the Quantum Information and Computing lab have continued with explorations in the exciting domain of generalised measurements or weak measurements. Strong measurements represent what they call "conventional measurements" wherein a measurement causes the system state to "collapse" to a certain state and any further evolution thus is affected by this measurement. In other words, once a quantum system is formulated, it is allowed to evolve under some unitary transformation after which it is measured. Any attempt to gain information in between preparation and measurement affects the system state. Weak measurements offer the possibility of gaining information about the system state in between preparation and measurement. This thus opens up a plethora of applications in theory and experiment and serves as a very useful tool in quantum mechanics. During 2018-19, G. Nirala, S. N. Sahoo, U. Sinha along with collaborator A. K. Pati have published a paper (Physical Review A 99 022111, 2019) in which they have been able to measure the expectation value of a non-Hermitian operator using weak values in a Mach Zehnder interferometer. Usually we are told that only Hermitian operators can be measured in the lab as their eigen values are real. However, by using weak values and weak measurements, one can also infer the expectation value of a Non-Hermitian operator. They had published the theory behind this claim in Physical Review in 2015 while their experiment on this was published this year. In this experiment, they have also introduced a novel scheme of measuring weak values in a Mach Zehnder interferometer without using weak measurements!

Quantum theory allows direct measurement of the average of a non-Hermitian operator using the weak value of the positive semidefinite part of the non-Hermitian operator. G. Nirala, S. N. Sahoo, U. Sinha and A. K. Pati have experimentally demonstrated the measurement of weak value and average of non-Hermitian operators by a novel interferometric technique. Their scheme is unique as one can directly obtain the weak value from the interference visibility and the phase shift in a Mach Zehnder interferometer without using any weak measurement or post selection. Both the experiments were performed with laser sources, but the results would be the same with average statistics of single photon experiments. Thus, this experiment opens up the novel possibility of measuring weak value and the average value of non-Hermitian operator without weak interaction and post-selection, which can have several technological applications.

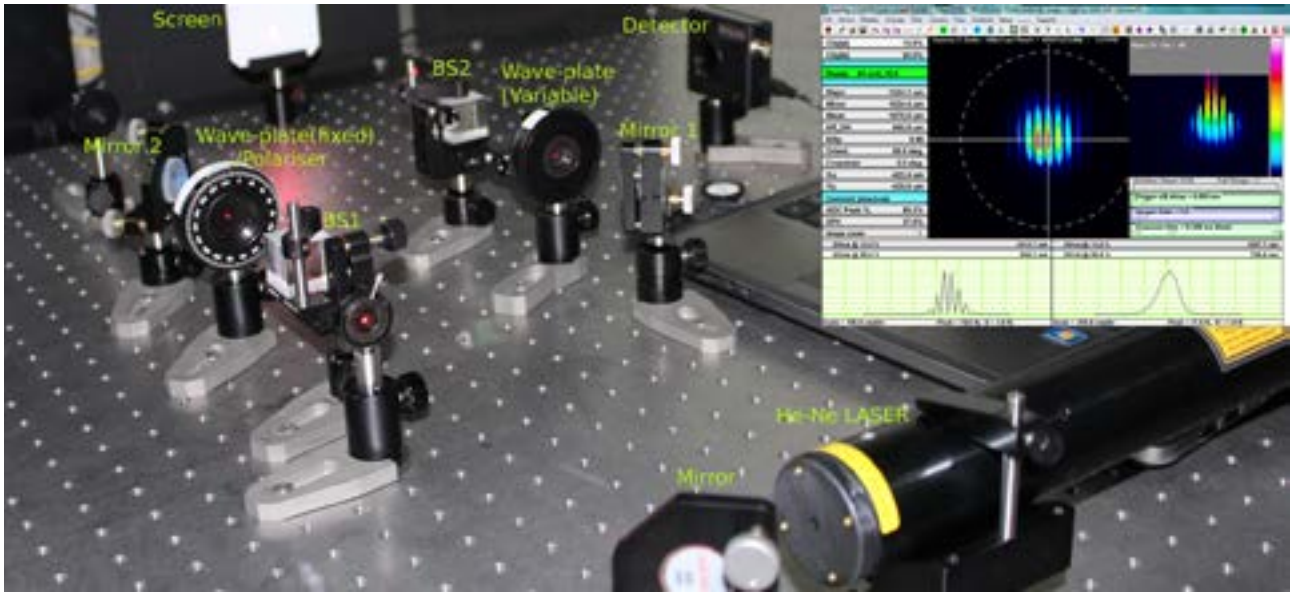
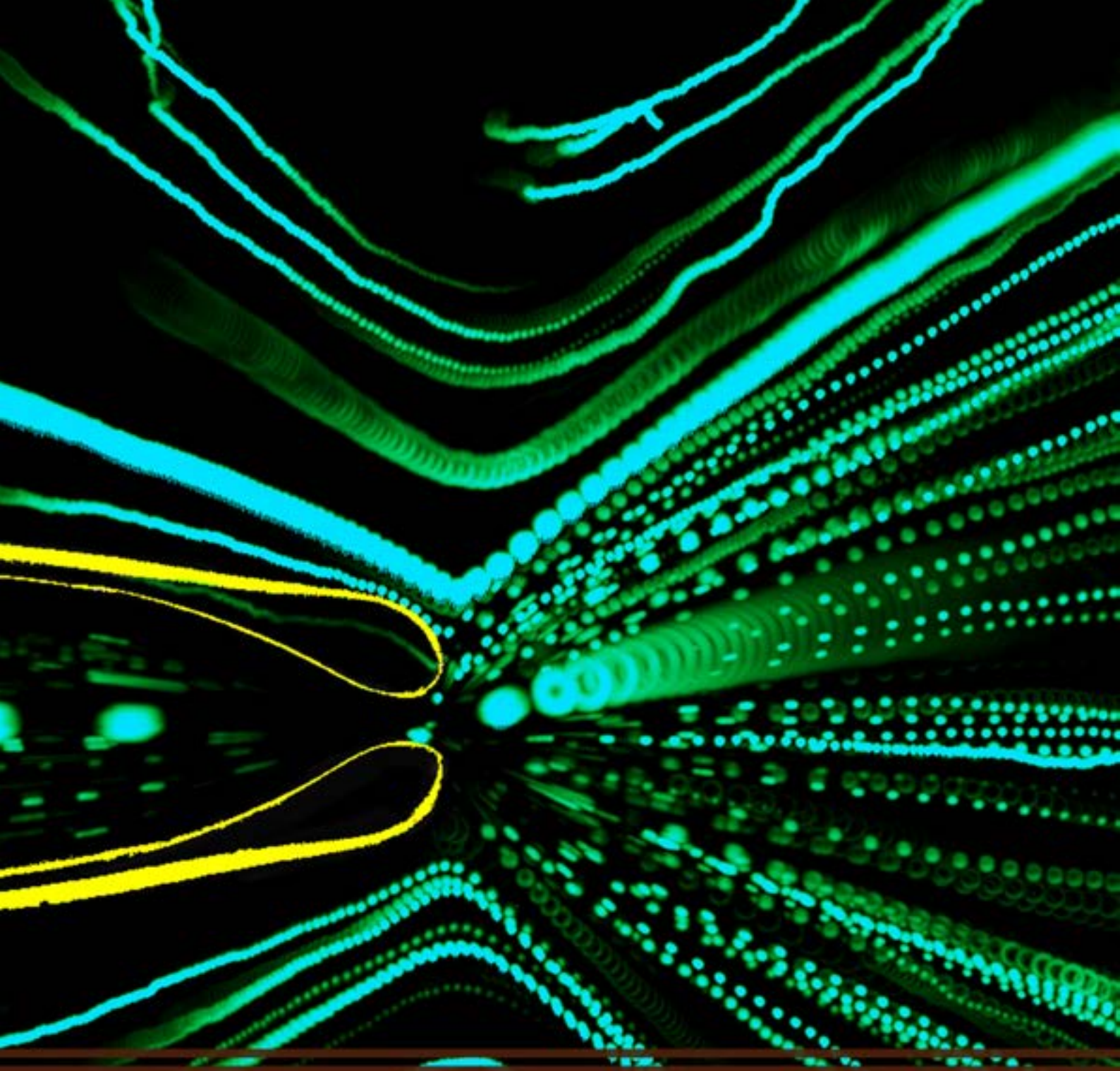


Figure 24. The experimental set-up in the lab which was used in the measurement of the average value of a non- Hermitian operator with weak value in a Mach Zehnder interferometer.
[G. Nirala, S. N. Sahoo, A. K. Pati (Harish-Chandra Research Institute, Allahabad) and U. Sinha]



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 2018-19

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 2018-19 was on design and synthesis of novel LC's and studying their physical properties, phase transitions and electro-optic properties of LC's, self-assembly in LC's, structure-property relationships of noble metal nanoparticle-LC hybrids and phenomenological theory of stability in fluid membranes and polymer crystallites.

Design, synthesis and physical studies of liquid crystalline and other materials

Charge Transport in Novel Phenazine Fused Triphenylene Supramolecular Systems

Novel phenazine–fused triphenylene discotic liquid crystals (DLCs) tethered with alkanethiols and alkoxy chains were synthesized during the past year by members A. Gowda, L. Jacob, Sandeep Kumar of the liquid crystal group at RRI along with collaborators Dharmendra P. Singh and Redouane Douali. The condensation of 4,5-dibromobenzene-1,2-diamine with triphenylene-1,2-diquinone discotic core, followed by the reaction with alkanethiols gave heterocyclic phenazine–fused triphenylene based DLCs. The intermediate dibromo– substituted phenazine and final alkanethiol substituted phenazine–fused triphenylene derivatives were found to exhibit a wide range of stable enantiotropic hexagonal columnar phase, which was characterised by polarized optical microscopy (POM), differential scanning calorimetry (DSC) and X-ray diffraction (XRD) studies. They further investigated the photophysical properties of all phenazine compounds using dilute solution of anhydrous chloroform. The charge carrier mobility was measured for one representative compound by time of flight method which revealed that

phenazine–fused triphenylene discotic mesogen exhibits p-type (hole) mobility of the order of 10^{-4} cm^2 V^{-1} s^{-1}. These novel mesogens exhibited a wide temperature stability with good charge mobility and optical properties. This work has demonstrated that these mesogens have potential applications in solar cells, sensors, organic light emitting diodes and other electro-optical device applications. This work was published in ChemistrySelect. (ChemistrySelect 2018, 3, 6551 – 6560)

[A. Gowda, L. Jacob, Dharmendra P. Singh (Université du Littoral Côted' Opale, France), Redouane Douali (Université du Littoral Côted' Opale, France), and Sandeep Kumar]

Hydrogen bond-driven columnar self-assembly of electroluminescent D–A–D configured cyanopyridones

During the past year, Sandeep Kumar and collaborator A. V. Adhikari and others have designed and synthesised a new series of flying bird-shaped liquid crystalline (LC) cyanopyridone derivatives with a D–A–D architecture, CPO-1 to CPO-4. They investigated the mesomorphic, photophysical, electrochemical, and electroluminescence characteristics in detail. Here, the H-bonding interactions through a central lactam core were shown to be the key driving force for their self-assembly into columnar

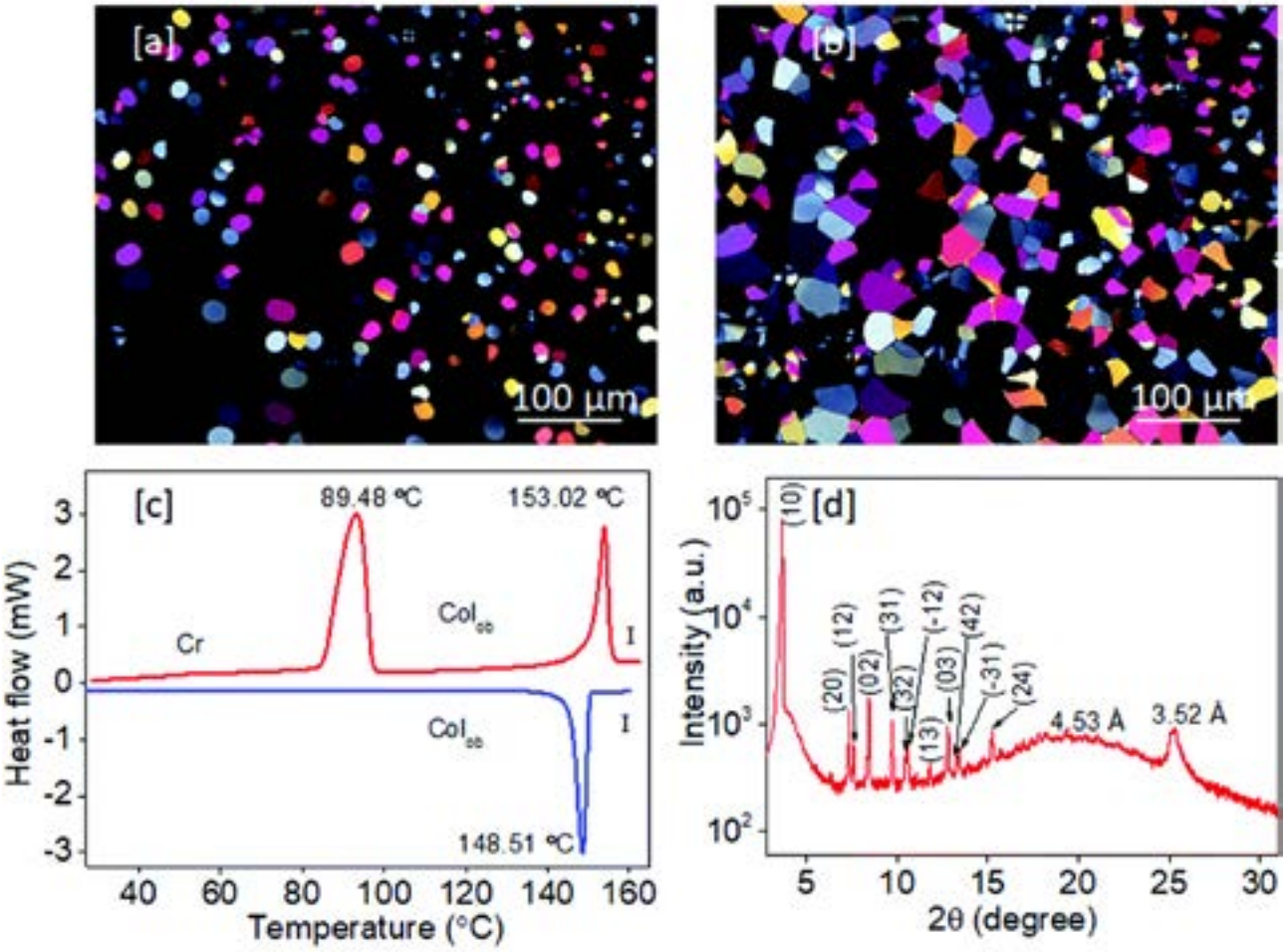


Figure 1. POM images of CPO-1: (a) at 150 °C and (b) at 30 °C upon cooling from the isotropic phase; (c) DSC thermogram of CPO-1 (red trace represents the heating cycle and blue trace represents the cooling cycle obtained at the rate of 5 °C min^{-1}under a nitrogen atmosphere); (d) XRD profile obtained for the Colob phase for compound CPO-1 at 144 °C.

mesophases. They confirmed the key role of H-bonding by using newly synthesized similar shaped compounds, MCP-1 to MCP-3. New CPO mesogens were found to be intense greenish blue light emitters with narrow band-gap energies. Conclusions were drawn based on theoretical studies also. Finally, the application potential of the selected mesogen CPO-2 as an emissive material was demonstrated for the fabrication of doped and non-doped OLED devices with different device architectures, which displayed encouraging results. In fact, this is the first reported use of emissive

H-bond-assisted columnar liquid crystals in devices. This work provides a new guideline and a versatile approach to the design of new LC molecules for the fabrication of efficient OLEDs.
[D. R. Vinayakumara (NIT, Surathkal), H. Ulla (IIT, Gauhati), S. Kumar, A. Pandith (Chonbuk National University, Republic of Korea), M. N. Satyanarayan (NIT, Surathkal), D. S. Rao (Centre for Nano and Soft Matter Sciences, Bangalore), S. K. Prasad (Centre for Nano and Soft Matter Sciences, Bangalore) and A. V. Adhikari (NIT, Surathkal)]

Supramolecular Self-Assembly of Ionic Discotic Liquid Crystalline Dimer with DNA at Interfaces

Nanoarchitectonics through ionic self-assembly at interfaces is an attractive approach to obtain advanced functional materials. During the past year, Sandeep Kumar and collaborator A. Nayak and others synthesised and investigated novel discotic dimer-DNA complex hybrid systems at air-water and air-solid interfaces. The ionic discotic liquid crystalline dimer consisted of two triphenylene cores linked via alkyl spacer with an imidazolium moiety. At air-water interface, the dimer formed a stable monolayer with a reversible collapse. The surface manometry results suggested that the condensed phase of the monolayer consisted of molecules arranged in an edge-on conformation. To understand the folding behaviour of the molecules, they carried out DFT calculations, which showed that the quantum chemically optimized folded-form of the molecule was electronically more stable than it's unfolded-form. Upon adding DNA to the subphase, a complex monolayer was formed with enhanced stability as was indicated by increased collapse pressure and decreased limiting area. Importantly, this complexation enabled an efficient and stable multilayer formation on silicon substrates with layers as many as 40. Since both DNA and discotic dimer molecules share common properties of one-dimensional charge transport with compatible structures, this complex film could serve as a model system for organic electronics.
[S. Mallik (IIT, Patna), A. Nayak (IIT, Patna), S. Daschakraborty (IIT, Patna), S. Kumar, K. A. Suresh (Centre for Nano and Soft Matter Sciences, Bangalore)]

Novel Annulated Triphenylene Discotic Liquid Crystals Generated by Pictet-Spengler Cyclization

Triphenylenes have been frontrunner in discotic liquid crystalline materials since their discovery. They possess great richness of mesomorphism in them. Chemists have been exploring this potential quite often by some substitutions in the core or periphery of the triphenylene molecule. In recent research work, SCM group members Marichandran Vadivel, I. Siva Kumar, K Swamynathan, V A Raghunathan and S. Kumar extended the triphenylene ring system by fusing with nitrogen and studied their mesomorphic and optical properties. They prepared four new compounds using Pictet-Spengler cyclization of hexaalkoxytriphenylene-1-amine with various aldehydes and characterized them using spectral and elemental analysis. Their mesomorphic properties were evaluated using polarizing optical microscopy, differential scanning calorimetry and X-ray diffractometry. These derivatives showed columnar hexagonal phase with great promise for further studies.
[Marichandran Vadivel, I. Siva Kumar, K Swamynathan, V A Raghunathan, S. Kumar]

Optoelectronic Exploration of Novel Non-symmetrical Star-shaped Discotic Liquid Crystals Based on Cyanopyridine

A novel family of non-symmetrical star-shaped cyanopyridine based discotic liquid crystals (CPBz6, CPBz8 and CPBz12) was designed and synthesized by SCM group members K. Swamynathan, Sandeep Kumar and collaborators D. R. Vinayakumara and A. V. Adhikari, as potential luminescent materials for optoelectronic applications. The length of one of the arms in the design was systematically varied to determine the structure–property relationships. All of

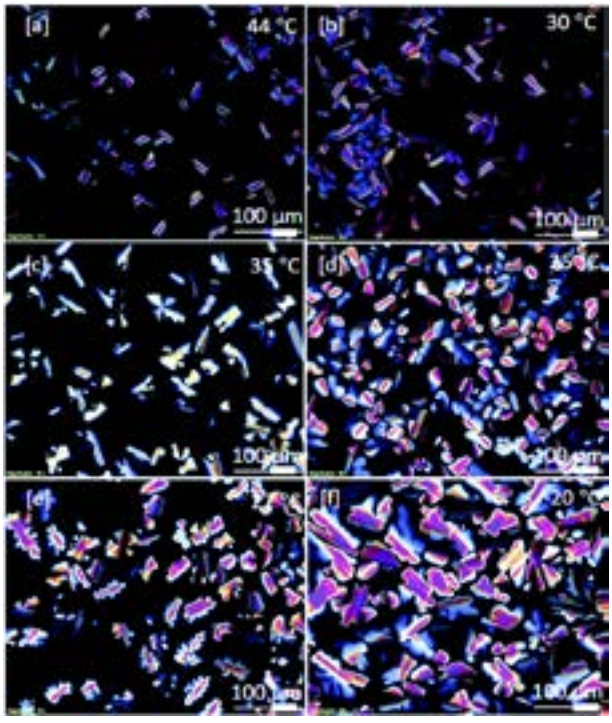


Figure 2. Polarized optical micrographs of the compounds: CPBz6 at (a) 44 °C and (b) 30 °C; CPBz8 at (c) 35 °C and (d) 25 °C; CPBz12 at (e) 27 °C and (f) 20 °C.

the compounds studied, exhibited a highly prospective ordered columnar mesomorphism stabilized at ambient temperature with advantageous very low isotropization

temperatures. Furthermore, they investigated their photophysical characteristics in depth, both in solution and in the liquid crystal (LC) state and found the discotics to be intense blue emitters with reasonably good quantum efficiency. Their dynamic intramolecular charge-transfer (ICT) behaviour was confirmed by steady-state absorption and fluorescence spectral analysis in varied solvent polarity. Furthermore, their electrochemical properties were studied from the combination of an experimental method and the theoretical simulations, which elucidated the low laying frontier molecular orbitals (FMOs) with a narrow energy band gap of ~2.0 eV. The resultant visually perceivable emission with favourable energy levels showcases their possible application in electronic display devices.
[D. R. Vinayakumara (NIT, Surathkal), K. Swamynathan, Sandeep Kumar, Airody Vasudeva Adhikari (NIT, Surathkal)]

Novel electron-deficient phenanthridine based discotic liquid crystals

Using Pictet-Spengler reaction between hexaalkoxytriphenylene-1-amine and various aryl aldehydes, A. R. Yuvaraj, Anu Renjith and Sandeep Kumar have synthesized nitrogen-containing polycyclic core 5-phenylnaphtho[1,2,3,4-lmn] phenanthridine and its nitro-functionalized positional isomers. The hexagonal columnar phase was observed in all the synthesized novel compounds. They carried out mesomorphic characterization using conventional thermal analysis and X-ray diffraction techniques and observed that under room temperature these compounds showed liquid crystal phase while no crystalline phase was observed even at −20 °C upon cooling from the isotropic temperature. Polarizing optical microscopy confirmed the long range of mesophase. Subsequently, charge transfer complexes were prepared by mixing the synthesized polycyclic hetero-aromatic compounds with 2,3,6,7,10,11-hexakis(octyloxy)-triphenylene. In UV-Vis absorption spectra, a redshift was found for the charge transfer complexes; which confirmed the interaction between donor-acceptor counterparts. They further measured the electrical conductivity of the charge transfer complexes and their pure target compounds.
[A.R. Yuvaraj, Anu Renjith and Sandeep Kumar]

Novel phenazine fused triphenylene discotic liquid crystals: synthesis, characterisation, thermal, optical and nonlinear optical properties

A straightforward synthesis of novel phenazine fused triphenylene discotic liquid crystals (DLCs) was realized during the past year by Ashwathanarayana Gowda, Litwin Jacob, Nithin Joy, Reji Philip and Sandeep Kumar. The condensation of 3,4-diaminobenzoic acid with a triphenylene-1,2-diquinone intermediate gives an acid derivative which upon esterification with aliphatic alcohols produces the corresponding monomeric ester derivatives of the phenazine fused triphenylene discotic liquid crystals. The intermediate acid derivative exhibited a rectangular columnar phase along with a high isotropic phase transition temperature. However, the monomeric ester derivatives showed a hexagonal columnar mesophase over a broad temperature range and was stable when decreased to room temperature upon cooling from the isotropic phase. The mesomorphic properties of the acid and monomeric ester derivatives of the phenazine fused triphenylene DLCs were characterised by polarised optical microscopy (POM), differential scanning calorimetry (DSC) and X-ray diffraction studies (XRD). The molecular structures of the intermediate and final compounds

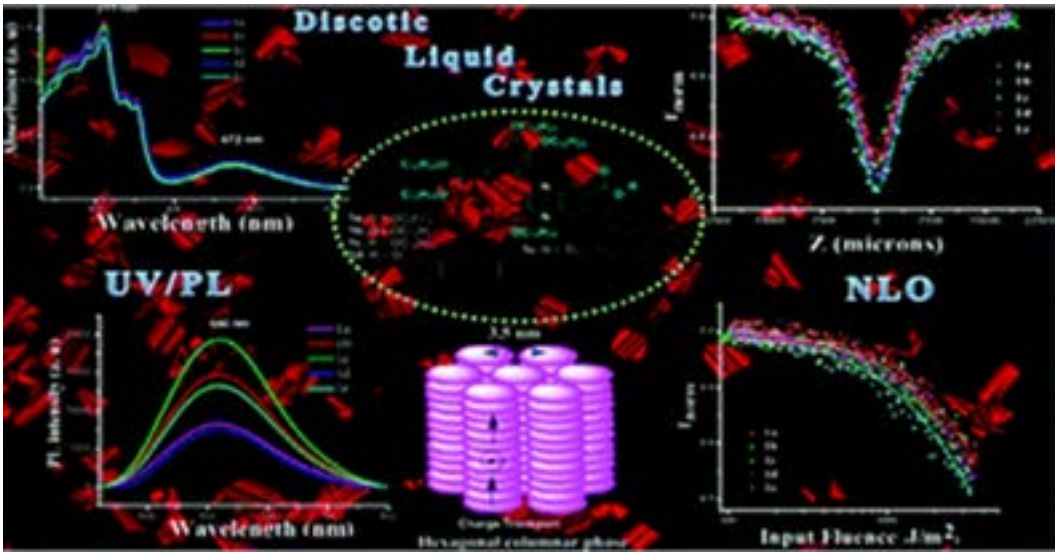


Figure 3. The graphical representation of novel π–extended phenazine fused triphenylene discotic liquid crystals shows enantiotropic columnar mesophase and good photophysical and nonlinear optical properties.

were characterised by spectral and elemental analysis. They investigated the photophysical properties of all the monomeric ester compounds in an anhydrous chloroform solvent and absorption bands around 291–472 nm and the corresponding emission bands at 658–661 nm were observed, respectively. The p-extended conjugation in these materials gives rise to high nonlinear optical properties. Through this work, they have shown the immense potential of these materials for use in electro-optical applications.
[Ashwathanarayana Gowda, Litwin Jacob, Nithin Joy, Reji Philip and Sandeep Kumar]

New fluorescent columnar mesogens derived from phenanthrene–cyanopyridone hybrids for OLED applications

The design, synthesis, and self-assembly of a novel series of pseudodiscoid dyads comprising electron-rich dialkoxyphenanthrene and trialkoxyphenyl rings appended to an electron-deficient cyanopyridone core was successfully accomplished by Sandeep Kumar and collaborator A V Adhikari and others. The studies showed that all the members of the series exhibited bi-mesophases with prospective columnar mesomorphism, which was steady under ambient conditions. The electro-optical studies revealed that the new liquid crystalline materials were efficient green light emitters both in solution and LC states with substantial chromaticity. Further, their theoretical studies (DFT) revealed that the molecules possess good intramolecular charge transport behaviour. These superior properties of the LC materials render them to become promising candidates for OLED applications. Their electroluminescence competence was also studied by fabricating doped and non-doped simple-architecture OLED devices with one of the doped devices with Py-2 as the emissive layer exhibiting the highest deep-green electroluminescence with a brightness of 1898 cd m^{-2} at 4.23 V having CIE coordinates of (0.312, 0.606).
[D. R. Vinayakumara (NIT, Surathkal), Hidayath Ulla (IIT, Gauhati), Sandeep Kumar, M. N. Satyanarayan (NIT, Surathkal) and Airody Vasudeva Adhikari (NIT, Surathkal)]

Scholl reaction of hexaphenylbenzenes with hexakis-alkoxy substituents

The hexakis-alkoxy substituted hexa-peri-hexabenzocoronene (HBC) discotic core is desirable aiming at strong π–π interactions in columns, electronic tuning of the core and better processability. The feasibility of synthesising a new hexakis-alkoxy substituted HBC core was investigated by Sandeep Kumar along with collaborator S K Pal and others. Experimentally, it was found that when two alkoxy substituents in a peripheral aromatic ring are placed meta to each other, the Scholl reaction results in fully cyclised HBC product. Surprisingly, when the alkoxy groups are ortho to each other, cyclodehydrogenation resulted in the formation of a partially fused product. This partially fused ring formation happened under varying reaction conditions and irrespective of the differing alkyl chain lengths. They attribute this to the considerable strain in the fully fused molecule from 1,2 isomer to cease the reaction at the partially fused stage. This hypothesis found support in quantum-mechanical calculations at the B3LYP/6-31G(d) level of theory. The incorporation of two electron-donating groups has also reduced the band gap compared to its mono alkoxy analogue. This reduction in band gap values seen in the synthesized samples is a step towards finding future applications of discotic liquid crystals in organic electronics.
[Shilpa Setia (IISER, Mohali), Sandeep Kumar, Debashis Adhikari (IISER, Mohali) and Santanu Kumar Pal (IISER, Mohali)]

Synthesis, mesomorphic properties and nonlinear optical studies of alkyl and alkoxy phenylacetylene containing phenazine fused extended triphenylene discotic liquid crystalline dyes

A. Gowda, L. Jacob, A. Patra, A. George, R. Philip and S. Kumar have reported the alkyl and alkoxy phenylacetylene containing phenazine fused triphenylene discotic liquid crystals (DLCs) which they obtained by the condensation reaction of triphenylene-1,2-diquinone with 1,2- diamino-4,5-dibromobenzene, followed by Sonogashira C–C coupling reaction with 4-alkyl-phenylacetylene or 4-alkoxy-phenylacetylene. They synthesized six novel derivatives and evaluated them for their thermal and optical properties. The derivatives showed a broad range of hexagonal columnar phase and retained their mesophase up to room temperature upon cooling from the isotropic liquid. Thermotropic liquid crystalline properties of all the compounds were studied by polarised optical microscopy (POM) and differential scanning calorimetry (DSC) while they employed X-ray diffraction (XRD) studies to understand the self-assembly of mesophase structure. Thermogravimetric analysis of all the mesogens revealed good thermal stability over a broad temperature range. The photophysical properties of the synthesized compounds were measured using UV–Vis absorption and photoluminescence emission spectroscopy in anhydrous chloroform solvent. The π-extended conjugation in these mesogens exhibited strong absorption bands falling around 270–487 nm and corresponding emission band at 657–663 nm respectively. The high delocalization of π– electrons in extended discotic mesogens showed high nonlinear optical properties when measured under excitation by nanosecond laser pulses at 532 nm. This property may enable these materials to find distinctive applications in the semiconducting devices.

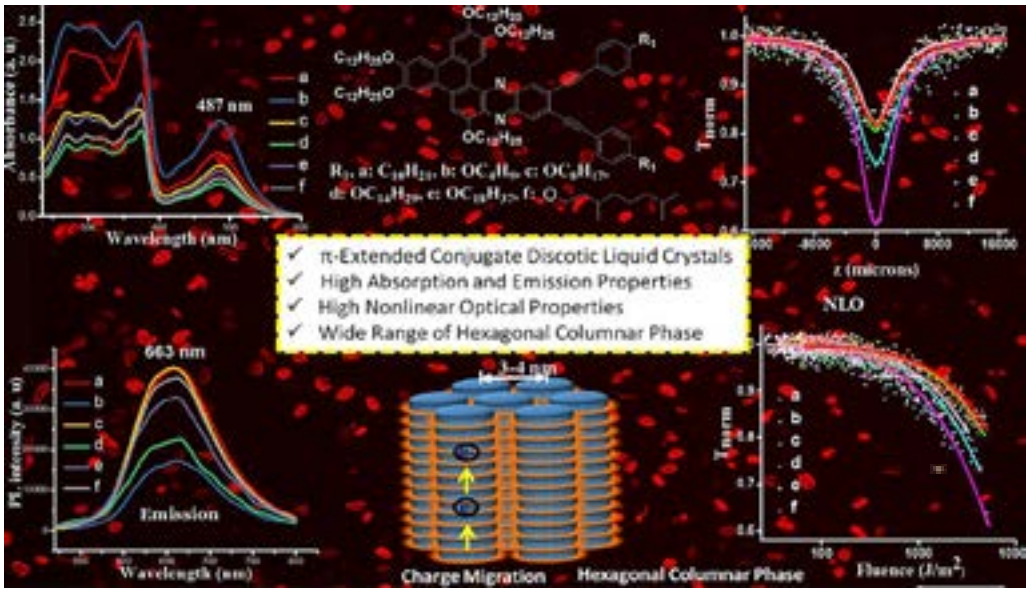


Figure 4. The graphical representation of alkyl and alkoxy phenylacetylene containing phenazine fused extended triphenylene discotic liquid crystals exhibit photophysical and nonlinear optical properties.
[A. Gowda, L. Jacob, A. Patra, A. George, R. Philip, S. Kumar]

Supramolecular Columnar Self-assembly of Wedge-Shaped Rhodanine Based Dyes: Synthesis and Optoelectronic Properties

The development of small π-conjugated functional organic molecules capable of forming supramolecular columnar self-assembly, is a rapidly growing area of material research. In this context, Sandeep Kumar and collaborator A V Adhikari have designed and synthesized a new series of wedge-shaped rhodanine derivatives with D-A configuration, viz. RA1– RA5 and studied their LC properties by employing DSC, POM and XRD techniques. They investigated the mesophase behaviour as a function of chain length, density and position of alkoxy terminals to understand the structure-property relationship. Interestingly, the longer chain analog, i.e. RA3 demonstrated H-bonded disc like macrocyclic structures, causing an imperative columnar hexagonal phase at ambient temperature. Further, their photophysical and electrochemical properties were evaluated. The derivatives showed a good dye property, which they attribute to effective intramolecular interactions, as confirmed by experimental and theoretical studies. This study has shown RA3 to be a potential candidate for applications in organic electronics.
[D.R. Vinayakumara (NIT, Surathkal), Sandeep Kumar, Airody Vasudeva Adhikari (NIT, Surathkal)]

Self-assembly of Taper- and Wedge-Shaped Maleimide Derivatives: Synthesis and Structure-property Relationship

Sandeep Kumar along with collaborator A V Adhikari and others undertook the design and synthesis of five new amphiphilic systems, viz. 10b-c and 11a-c composed of maleimide at the focal point and alkoxy phenyl ring at the periphery. Their self-assembling behaviour was examined systematically by varying the length of hydrophobic part and aromatic core segment. Evidently, on increasing the aromatic core length, maleimide-based amphiphiles relatively emerged as two distinct molecular structures, i.e. wedge- and tapered-shaped. The mesomorphic studies of the two series revealed that, tapered shaped maleimide derivatives assemble into a smectic A phase with an interesting phasmidic arrangement, whereas the wedge-shaped molecules exclusively formed a prospective supramolecular hexagonal columnar mesophase through the intermolecular hydrogen-bonding via maleimide head group. These self-assembled materials could demonstrate high-sensitivity towards various external stimuli.
[D R Vinayakumara (NIT, Surathkal), Sandeep Kumar, Krishna Prasad (Centre for Nano and Soft Matter Sciences, Bangalore) and A. V. Adhikari (NIT, Surathkal)]

Nematic and switchable intercalated phases with polymerizable bent-core monomers

Liquid crystals (LCs) formed by achiral bent-core (BC) molecules have evoked much interest due to their association with chirality and polar order. Lamellar and columnar phases formed by BC molecules are usually electro-optically switchable and nematic (N) phases have the possibility of being biaxial or polar. Polymeric LCs exhibit interesting properties which can have practical applications ranging from photonics to non-linear optics. In view of this, H. T. Srinivasa, N Prutha and R Pratibha have used a novel

type of molecular architecture to obtain polymerizable bent-core monomers by introducing naphthalene moiety in the side arms and linking them with terminal double bonds as polymerizable functional groups. It was shown that the phase sequence can also vary drastically depending on the central core. Optical, x-ray diffraction, dielectric and electro-optic studies have shown that while the phenyl ring at the centre (compound 6B2) stabilizes a new form of switchable intercalated phase, having the naphthalene moiety at the centre (compound 6N2) promotes a long-range nematic phase.

Several BC molecules derived from 2,7-dihydroxynaphthalene have been reported and found to exhibit different types of polar smectic and columnar phases as well as N phases. However, the naphthalene moiety has always been used as the central core but not in the side arms. It can be expected that along with the central core, the rigidity of the side arms can also influence the occurrence of unusual phase sequences. Therefore, the effect of introducing naphthalene moiety in the side arms was investigated. In addition, the molecular structural design also involves introduction of polymerizable sites as this can lead to switchable polymers built up of BC molecules. For comparison, a compound with a similar molecular architecture having naphthalene moiety in the side arms but with a central phenyl core was also studied.

The experimental results have shown that the compound with the central phenyl core and naphthalene moiety in the side arms exhibited an intercalated structure. Usually the intercalated B_6 phase is known to be electro-optically non-switchable. The response to the electric field in Sm_{int} phase of 6B2 suggests that the detailed structure in this phase may be different from that in the B_6 phase. The formation of a rectangular lattice conforming to a *cmm* space group symmetry similar to that in switchable B_{1rev} phase, in the B'_{1rev} phase obtained on cooling the Sm_{int} phase implies that the organization of molecules may be similar to that in the B_{1rev} phase with the density modulation being present in the plane perpendicular to the polarization vector. This is most likely because the bulky naphthalene moiety in the side arms prevents the organization of the columns with the axis perpendicular to the bend direction of the molecules. Molecular rotation therefore becomes possible as the intercalation is not so compact and electro-optic switching can be observed in the Sm_{int} phase. However, the P_s value is not very high due to the heavier side arms of the aromatic core.

The N mesophase formed by BC molecules can result due to a widening of the bend angle. This condition appears to be satisfied when the naphthalene moiety is present at the centre. In addition, the bulky naphthalene moiety in the side arms renders the molecules less prone to polar packing in the layers leading to the formation of a stable N mesophase. An interesting feature observed in the N phase is the striking variation in transmitted colour arising due to the changes in the effective birefringence as the sample was cooled (Figure 5). This shows that conformational changes could affect the orientation of the BC molecules substantially with decrease in temperature, as the long axis of the BC molecules reorient to form the columnar B_1 phase. The variation of transmitted colour within the nematic phase could be utilized in liquid crystal based optical sensors.

[H T Srinivasa, N Prutha and R Pratibha]

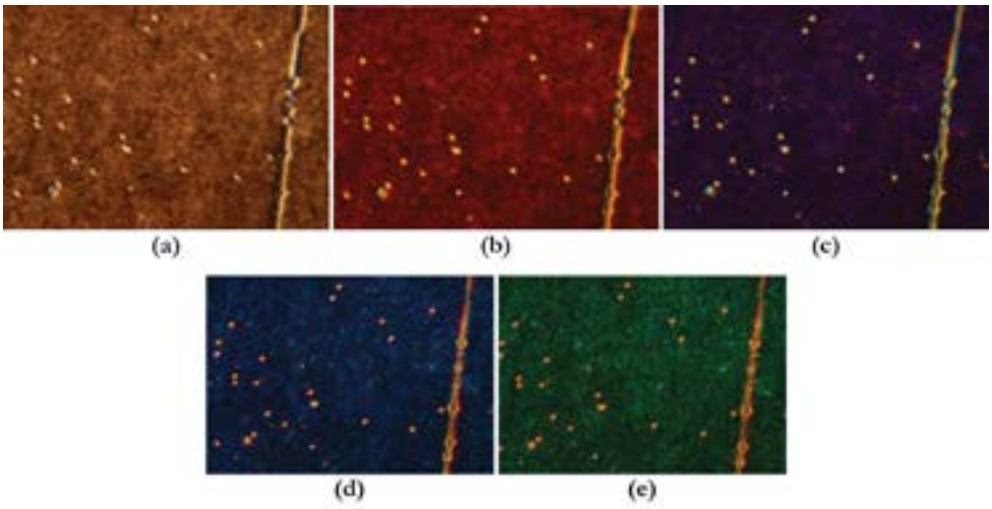


Figure 5. Optical textures observed in the nematic phase of 6N2 at different temperatures (a)186 °C, (b) 183.5 °C, (c) 180 °C, (d)176 °C and (e)170°C.

Unusual forms of liquid crystal-fibre self-assembly

The interaction between liquid crystals (LCs) and fibrous structures can result in novel forms of self-assembly leading to interesting nanostructured materials. One of the most well established examples of such a self-assembling process is found during the formation of liquid crystalline physical gels. However, most often the fibres are randomly dispersed in the LC matrix. On the other hand, controlled and well-ordered fibre assemblies have the potential to be used as templates for positioning nanomaterials, widening the scope and functionality of the gels. In principle the alignment direction of the fibres can be parallel or perpendicular to the LC director and can depend on the intermolecular interactions between LC and gelator.

Neha B. Topnani, Prutha N. and Pratibha R. along with collaborator Igor Musevic had earlier reported self-assembly of elongated fibrous aggregates of a simple alkanoic acid organogelator 12-Hydroxy stearic acid (12-HSA) within the nematic (N) phase formed by E7 which is mixture of four cyanobiphenyls which resulted in a very interesting grating-like structural motif composed of LC rich and fibre rich regions whose dimensions can be varied depending on the relative concentration of the NLC and the gelator. In this case the segregation into LC rich and fibre rich regions was attributed to the strong association between the molecular dimers of the cyano biphenyl compounds which remain unaltered even in the N-gels and in turn encourages enhanced gelator-gelator interactions via intermolecular hydrogen bonding rather than the solvent-gelator interactions.

During the past year they have undertaken detailed investigations on the influence of LC alignment on the fibre self-assembly. Preliminary studies have shown that when a mixture of nematic LCs formed by bicyclohexyl)-4 β-carbonitrile compounds which do not form dimers, is gelated with 12-HAS, the fibres orient orthogonal to the LC director and also give rise to a systematic distribution of very different type of defect structures. The influence of these on the strength and stability of the N-gels is currently being investigated.
[Neha B. Topnani, Prutha N., Igor Musevic (J. Stefan Institute, Ljubljana, Slovenia) and Pratibha R.]

Phase transition and electro-optics of liquid crystals

Electric field induced transition in axial polar tilted smectic liquid crystal exhibited by bent core hockey stick shaped molecules

Liquid crystals are class of soft materials characterized by the presence of orientation order of the constituent molecules. The orientation order can be easily deformed by externally applied electric field giving rise to various electro-optic effects of liquid crystals which are being exploited for different liquid crystal devices for various applications. Recently, Deepshika Malkar, Arun Roy along with collaborator Veena Prasad have discovered a new type of smectic liquid crystal phases exhibited by bent core hockey stick shaped molecules and have performed detailed experimental studies on the electro optic properties of these new smectic phases. They measured field-induced changes in the birefringence of a planar-aligned sample of thickness 5µm. When they cooled the sample slowly from isotropic phase to the smectic phase under cross polarizer in a polarizing microscope they observed a smooth conic fan texture as shown in Figure 6(a) in the absence of applied electric field. The dark extinction brushes in the fan region were visible parallel and perpendicular to the polarizer, which is indicative of the optic axis being parallel to the layer normal in the Smectic C phase and conforms to the anticlinic tilt of the molecules in successive layers. The changes in the colour of the sample with increasing amplitude of the applied AC voltage is shown in Figure 6(b-d). The change in the colour of the sample without any rotation of the extinction brushes with increasing amplitude of the applied voltage is indicative of the variation of birefringence of the sample under electric field. Interestingly, it was found that upon increasing the applied voltage, birefringence colour starts to change beyond a threshold voltage. On further increasing the applied voltage, the birefringence colour changed gradually from purple to blue colour (Figure 6(b-c). At even higher voltages, the birefringence colour changed to green (Figure 6(d)) and the colour change tends to saturate. A theoretical model has also been developed to account for the observed effects.

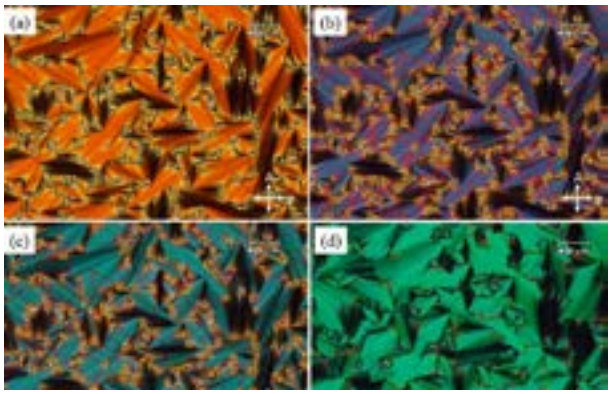


Figure 6. The changes in the color of the sample under the application of an AC voltage of frequency 1 kHz with increasing amplitudes (a) 0 V (b) 22 V (c) 43 V and (d) 80 V at 115^{0}C in Smectic C phase.
[Deepshika Malkar, Veena Prasad (CeNS, Bangalore) and Arun Roy]

N-Sm A-SmC phase transitions probed by a pair of elastically bound colloids

When foreign particles are dispersed in a uniformly aligned nematic liquid crystal the average orientation of the molecules (i.e., the director) is locally deformed around the particles due to the strong surface anchoring. Each particle stabilizes topological points or loop defects creating an elastic deformation in the surrounding medium. The deformation increases the elastic energy of the liquid crystals. When the distortion regions of two physically separated particles tend to overlap they exhibit long-range elastic interaction. The interaction energy is anisotropic. The system of particles minimizes the total elastic energy by sharing the orientationally deformed regions associated with the particles and based on this principle various interesting two- and three-dimensional colloidal assemblies have been reported.

When the colloidal particles are dispersed in a smectic liquid crystal, the situation is very different due to the translational order in addition to the orientational order of the molecules. The surface anchoring of the smectic layers at the colloid's surface is not well defined and understanding of the induced defects and equilibrium separation among the particles is incomplete. Arun Roy and collaborators Muhammed Rasi M., K. P. Zuhail and Surajit Dhara performed experimental studies on a pair of colloids with planar and homeotropic surface anchoring across the N-SmA-SmC phase transitions. Their study shows that the temperature dependence of the equilibrium separation and the angle of the colloid pair with respect to the far field director depend on the type of surface anchoring and are highly sensitive to the elasticity and SmC order parameter.

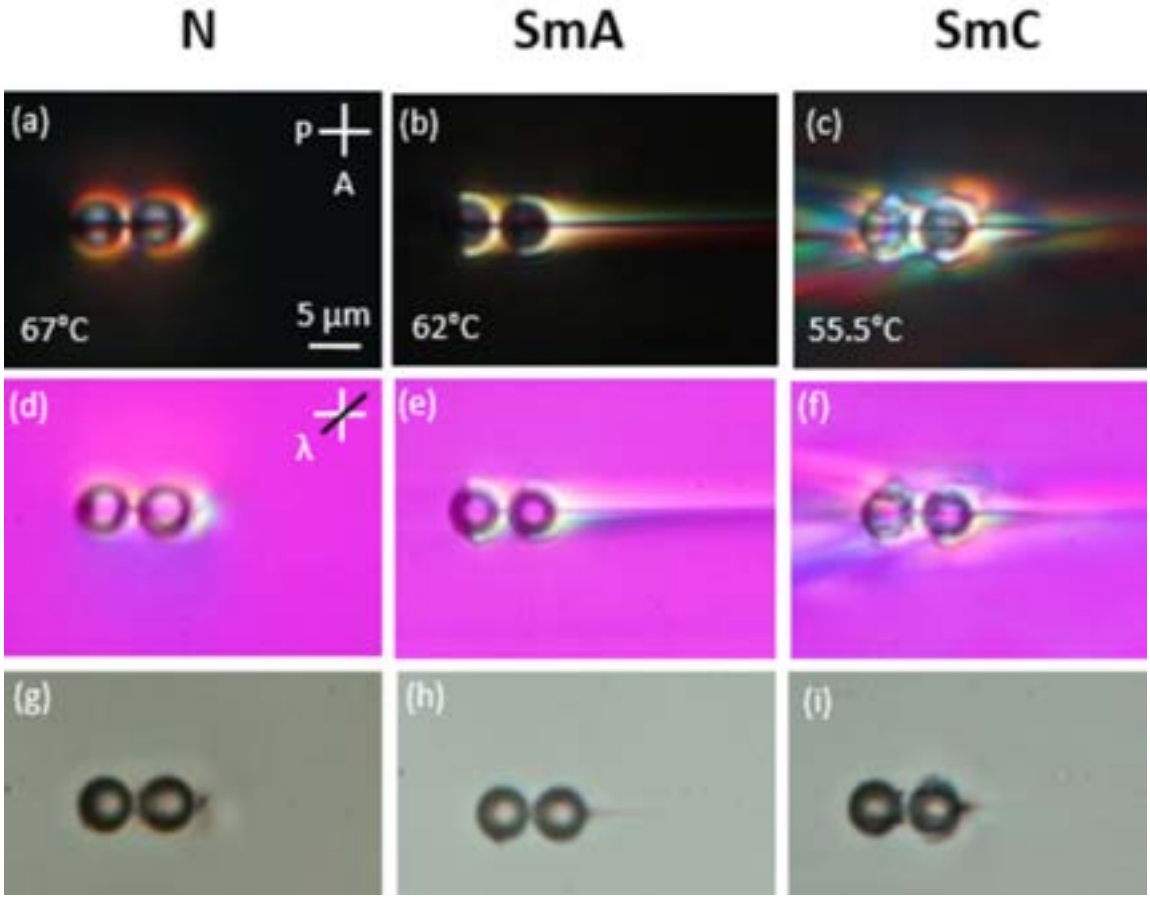


Figure 7. Optical photomicrographs of a pair of collinear colloids with homeotropic anchoring at different temperatures in a planar cell. Images are taken (a–c) with crossed polarizers, (d–f) with crossed polarizers and a λ-plate, and (g–i) without polarizers and the λ-plate. Cell thickness and diameters of the colloids are 5.2 µm and 14 µm, respectively.

[Arun Roy and collaborators from the University of Hyderabad: Muhammed Rasi M., K. P. Zuhail, Surajit Dhara]

Liquid crystalline blue phases

Clusters of B_7 fibres reveal origin of Blue phase stability in a binary mixture of chiral rod-like and achiral bent-core molecules

Liquid crystal (LC) blue phases (BPs) have gained relevance due to their potential applicability as tunable photonic band gap materials. However, their narrow temperature range often restricts technical usage. Doping with an LC made of achiral bent-core (BC) molecules is one of the strategies employed to increase BP stability. Prutha N. and Pratibha R. have, during the past year, designed a new type of binary system by doping a BCLC exhibiting the polarization modulated lamellar B_7 phase into a calamitic chiral LC made of rod-like (R) molecules and exhibiting a very short range BP and found that the B_7 phase in which macroscopic chirality is manifested in the form of helical filaments to be instrumental in increasing the BP range considerably. In addition, the formation of B_7 fibres within the chiral nematic (N^*) phase occurring below the BPs in this system, has provided direct visual evidence that islands rich in BC molecules lie interspersed between the double twist cylinders (DTCs) formed by the R molecules. Based on several experimental studies, they have shown that the BP stability in this system may be attributed to an interplay of conformational and intrinsic chirality of the BC and R molecules across the interface of these islands.

As the sample cooled from the isotropic phase the pronounced size difference between the BC molecules with extremely long alkyl chains and the shorter R molecules, initially led to viscoelastic phase separation resulting in the expulsion of the BC molecules in the form of islands embedded in a matrix of highly chiral R molecules forming double twist cylinders, characteristic of BPs. At this stage small angle x-ray scattering (SAXS) did not show any reflections and only the wide angle liquid peak was observed showing that lamellar order is not established in the islands of BC molecules and their polar directions are randomly oriented (Figure 8a).

Both theoretical and experimental studies have shown that BC molecules can exist in strongly chiral conformations and both left handed and right handed conformations are highly probable. Minimum energy conformer search for the BC molecule, also suggests the presence of conformational chirality. Initially when the islands composed of mainly BC molecules form, conformers with either left or right handed twist senses may be present. However, the ratio of the two conformational states can be biased by external influences. It has been shown theoretically that in the N^* phase formed by chiral host molecules doped with BC molecules, chiral interactions can influence the conformations of the BC molecules and in turn, alter the enantiomeric excess. This can lead to an overall increase in the number of chiral molecules, which can reduce the helical pitch. The host chiral R molecules can also influence the enantiomeric excess of the BC molecules and the helical pitch can be affected as evidenced by the selective reflection measurements.

With decrease in temperature the lamellar order starts building up within the islands of BC molecules which is also shown by SAXS, with the *d* spacing at the temperature at which the fibres form being close to that observed in the B_7 phase of the pure BC compound. The synchronization between molecules possessing conformations with similar twist sense can be expected to be enhanced across the interface between the helical structures formed by the chiral R molecules and the BC molecules within the islands resulting in a better packing efficiency of the BC molecules with a ferroelectric order within the lamellae (Figure 8b). This prompts an escape from macroscopic polar order within such a lamellar phase leading to a polarization splay coupled with layer modulation (Figure 8c), resulting in the B_7 phases and in the expulsion of the fibres from the islands of BC molecules.

The spontaneous expulsion of B_7 fibres (Figure 9a), which can usually be obtained only by mechanical pulling with a needle, is an interesting offshoot of this study. Another interesting feature which is different from the free standing B_7 fibres is that each of the fibres forming the clusters (primary cluster) in this system have smaller groups of short fibres (secondary cluster) present in bunches all along the length of the main fibre. In order to gain insight into the structure of the B_7 fibres and also the distribution of the fibre clusters, the self-assembly and morphology was monitored using Cryo-Scanning electron microscopy (Cryo-SEM) (Figure 9b). Dielectric and electro-optic studies show the electro-responsive nature of the fibres. The transition between two types of B_7 phases within the confines of the fibres is an additional novelty.

The sequential changes in the molecular organization traced by various experimental probes like textural observations, thermal analysis, selective reflection measurements and X-ray diffraction studies has provided a clear insight at the molecular level and can aid in designing new materials for obtaining BP stability for photonic applications. On the other hand, extraction and dispersal of the spontaneously formed uniform electro-responsive B_7 fibres into a suitable matrix may also have the potential to form new materials. A manuscript based on these studies has been recently submitted.

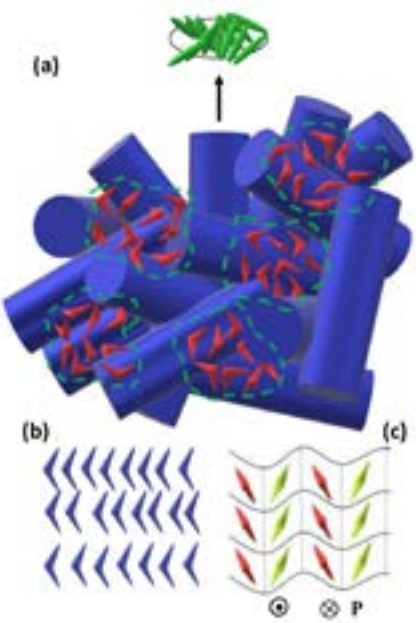


Figure 8. Schematic representation of (a) islands composed of randomly oriented BC molecules interspersed between chiral R molecules forming DTCs. (b) Lamellar arrangement formed by the BC molecules within the islands. (c) Layer undulations in the B7 phase.

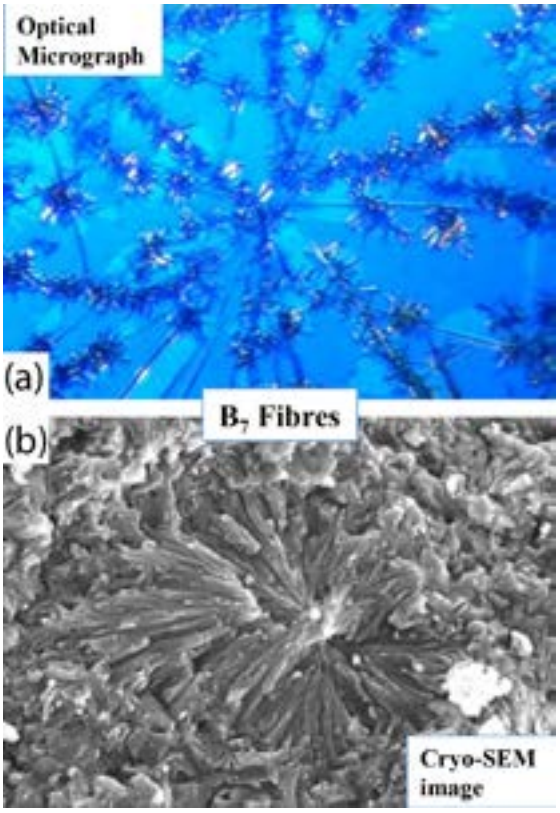


Figure 9. (a) Optical texture of a B7 fibre cluster formed in the N* phase between crossed polarizers (b) Cryo-SEM image of a secondary B7 fibre cluster.

[N. Prutha and R. Pratibha]

Liquid crystal nanoscience

Lyotropic liquid crystals of CdS nanoribbons

During the past year, SCM group members A. B. Shivanandreddy, M. Kumar and S. Kumar have observed the formation of highly ordered lyotropic liquid crystalline phase of CdS nanoribbons of different length scales. It was observed that selective wetting of the capping alkyl chains induces mobility in them leading to the formation of lyotropic liquid crystalline phase. They characterized this self-organization by X-ray diffraction studies, polarized optical microscopy, differential scanning calorimetry and Cryo-SEM techniques. Their results indicate that these CdS nanoribbons aggregate in presence of cyclohexane to form rod like (Cds-50 and CdS-60) to rope like (CdS-70) supramolecular structures. These liquid crystals showed the presence of long-range orientational order and positional order. The majority of work so far on lyotropic liquid crystals has been confined to organic molecules; this study ventures into relatively less explored field of lyotropic phases in inorganic materials.

[A. B. Shivanandreddy, M. Kumar, S. Kumar]

Dependence of physical parameters on the size of silver nano particles forming composites with a nematic liquid crystalline material

Thermodynamic, dielectric and electro-optical properties of a nematic liquid crystal namely 4-(trans-4-nhexylcyclohexyl) isothiocyanatobenzoate (6CHBT) mixed with silver nanoparticles (Ag-NPs) of two widely different sizes was studied by Sandeep Kumar along with collaborator R Dhar and others. They carried out thermodynamic studies which suggested nominal increase in isotropic to nematic transition temperature of the nano composites as compared to the pure 6CHBT. Dielectric parameters of nano composites in the homeotropic and planar aligned samples were measured in the frequency range of 1 Hz–35 MHz. Dielectric studies suggested that anisotropy is marginally decreased due to the dispersion of Ag- NPs. Threshold voltage for Freedericksz transition and splay elastic constant decreased in the case of nano-composites. Dielectric studies also suggested that relaxation mode corresponding to the molecular rotation about its long axis couldn't be detected in the experimental frequency window. However, a relaxation mode due to the molecular rotation about its short axis was obtained.

[P. Tripathi (University of Allahabad, Allahabad), M. Mishra, S. Kumar, R. Dabrowski (Military University of Technology, Poland), R. Dhar (University of Allahabad, Allahabad)]

Liquid Crystals Decorated Gold Nanoparticles for the Photoswitching Properties

Sandeep Kumar along with collaborator Md. Lutfor Rahman and others has synthesized liquid crystals decorated gold nanoparticles in a molecular architecture consisting of the azobenzenes moieties with alkene as the peripheral units, connected to gold nanoparticles (Au-NPs) via thiolated phenolic units in the middle. They investigated the morphology and mesomorphic properties of the synthesized hybrid using field emission scanning electron microscope, high-resolution transmission electron microscopy, differential scanning calorimetry and polarizing optical microscopy. Their investigation led to the following observations: the aromatic thiolated azobenzene moieties with gold nanoparticles showed smectic A phase with monotropic nature appearing in the cooling cycle. HR-TEM measurement showed that the functionalized Au-NPs are well dispersed without any aggregation. However, the absorption spectrum of peripheral azobenzene units shows strong absorption maxima in the ultraviolet region at 378 nm due to π-π^* transition. For n-π^* transition, a weak absorption band was observed in the visible region at 472 nm. The photo-isomerization characteristic was measured using absorption spectroscopy. The photosaturation of Au-NPs was found at the time duration of 16 s. The thermal back relaxation was completed after the time interval of 70 min. Moreover, Au-NPs showed excellent stability towards photo-decay. This study has demonstrated that Au-NPs compound is suitable in the field of optical storage and molecular switching.

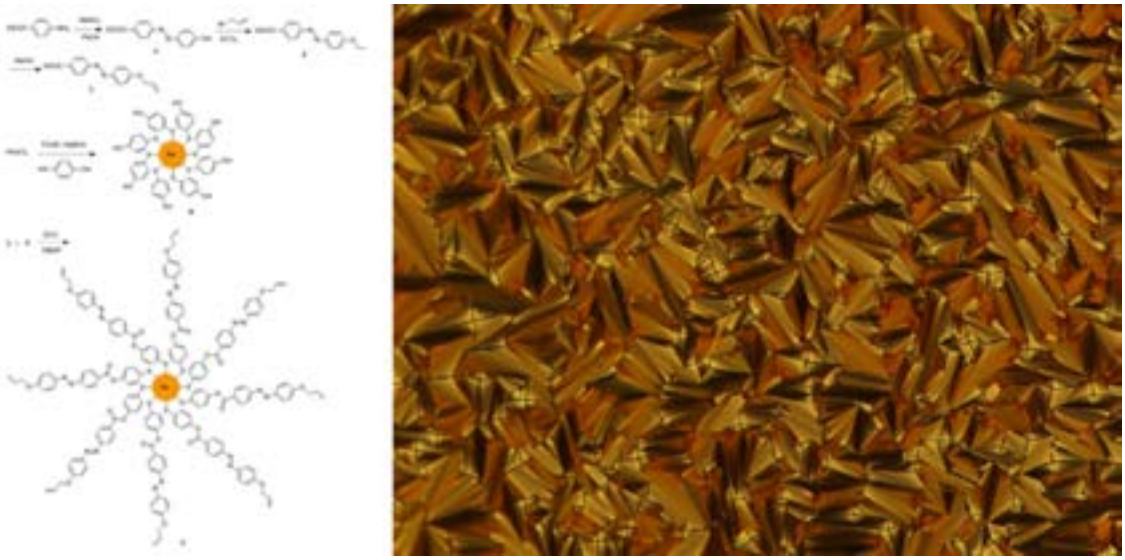


Figure 10. (Left) Gold NPs functionalized using azobenzene moieties with terminal alkene. (Right) Optical micrographs of compound 5 on cooling from the isotropic liquid and texture of SmA phase taken at 90°C.

[Md. Lutfor Rahman (Universiti Malaysia Sabah, Malaysia), Mohd Sani Sarjadi (Universiti Malaysia Sabah, Malaysia), Shaheen M. Sarkarb (Universiti Malaysia Pahang, Malaysia), Mashitah M. Yusoff (Universiti Malaysia Pahang, Malaysia), A. R. Yuvaraj and Sandeep Kumar]

CdSe quantum dots in chiral smectic C matrix: experimental evidence of smectic layer distortion by small and wide angle X-ray scattering and subsequent effect on electro-optical parameters

During 2018-19, Sandeep Kumar and collaborators dispersed CdSe quantum dots (QDs) in a ferroelectric liquid crystal (FLC) and studied the hybrid using small and wide-angle X-ray scattering and atomic force microscopy to understand the molecular organization in chiral smectic C (SmC*) phase. Following are some observations that resulted from their study: Small angle X-ray scattering indicated that the presence of QDs causes enhancement in the smectic layer separation. The smectic order parameter for neat FLC and FLC–QDs mixtures was in the range of 0.6 to 0.85. They found both smectic order parameter and structural tilt to be lesser for FLC–QDs mixtures as compared to neat FLC. The insertion of QDs in SmC* matrix caused localized smectic layer distortion in such a way that spontaneous polarization remains almost the same but the electro-optic switching of molecules becomes faster. Their work has outlined the superiority of FLC–QDs mixtures for electrical energy storage and their suitability in electronic devices.

[D. P. Singh (Université du Littoral Côted' Opale, France), R. Visvanathan (University of Colarado, Boulder), A. E. Duncan (University of Colarado, Boulder), B. Duponchel (Université du Littoral Côted' Opale, France), Y. Boussoualem (Université du Littoral Côted' Opale, France), S. Kumar, N. A. Clark (University of Colarado, Boulder), J.-F. Blach (Universite Artios, CNRS, France), R. Douali (Université du Littoral Côted' Opale, France), & A. Daoudi (Université du Littoral Côted' Opale, France)]

Synergistic effect of hybrid Ce3+/Ce4+ doped Bi_2O_3 nano-sphere photocatalyst for enhanced photocatalytic degradation of alizarin red S dye and its NUV excited photoluminescence studies

Using a simple solid-state reaction route Sandeep Kumar along with collaborators L Parashurama and others have synthesized highly spherical structured Ce3+/ Ce4+ doped Bi_2O_3 nanosphere photocatalyst. Since the crystallite phase of a photocatalyst plays an important role on its activity, the phase of the catalyst was suitably tuned by varying cerium concentration and calcination temperature. Their experiments showed that, 9 wt% cerium doped Bi_2O_3 calcinated at 600°C showed better photocatalytic performance for the degradation of Alizarin red S dye. They explain that the enhanced performance of this optimized catalyst is due to synergistic effect by the presence of inter convertible Ce3+/Ce4+ oxidation states and mixed α-β phase Bi_2O_3. Addition of EDTA-2Na and radical scavengers (Benzoquinone, t-BuOH) decreased the photocatalytic efficiency, indicating that, the presence of O_2, O_2- and OH radicals and their significant role in the degradation of ARS dye. Through this work, they have proposed a plausible mechanism and degradation pathway of ARS degradation.

[S. Akshatha (Tumkur University, Tumkur), S. Sreenivasa (Tumkur University, Tumkur), L. Parashurama (New Horizon College of Engineering, Bangalore), V. Udaya Kumar (Siddhaganga Institute of Technology,Tumkur) , S.C. Sharma (Jain University, Bangalore), H. Nagabhushana (Tumkur University, Tumkur), Sandeep Kumar, T. Maiyalagan (SRM Institute of Technology, Chennai]

Magnetic field dependence of the hexagonal to isotropic transition temperature of a single-walled carbon nanotubes dispersed lyotropic liquid crystal

Electrical conductivity studies undertaken by Vijayaraghavan D., Jai Mishra and R. Thejas on single-walled carbon nanotubes dispersed lyotropic liquid crystal

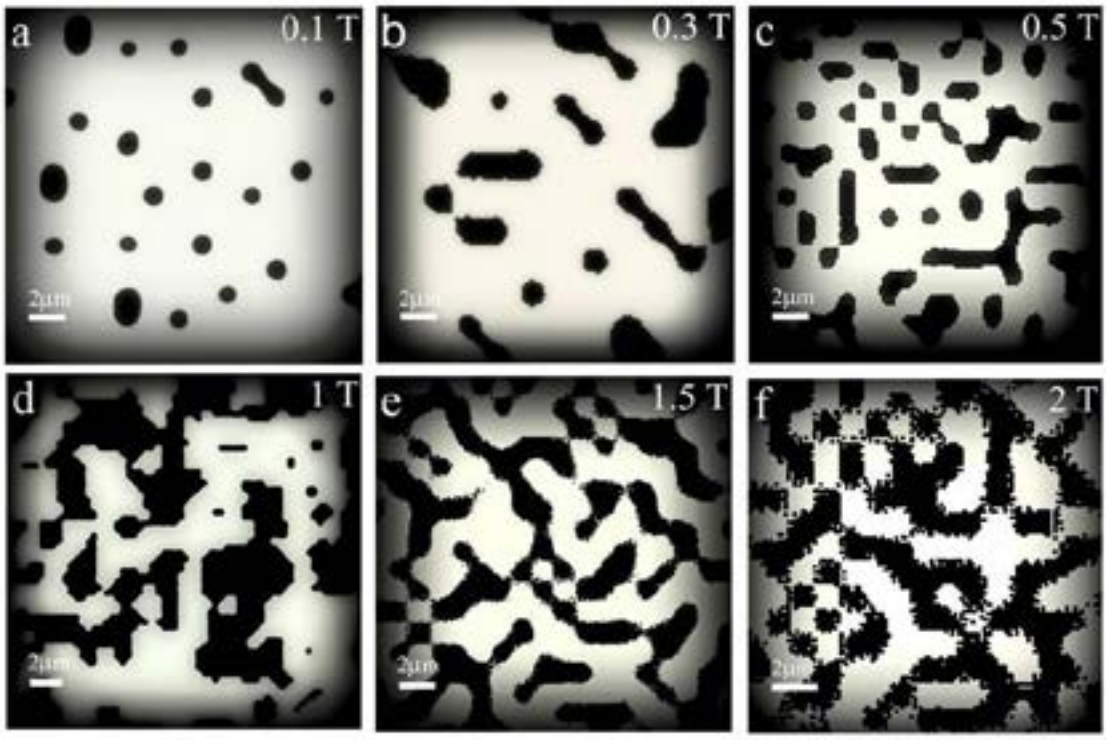


Figure 11. Optical images of the LLC-CNT system for various applied magnetic fields. Spherical and rod-like CNT aggregates are seen for 0.1 and 0.3 T respectively (Figures 11a and 11b). For higher applied fields 0.5 to 1 T large CNT aggregates are seen (Figures 11c and 11d). For 1.5 T, the large CNT aggregates disintegrate and exhibit hook-like aggregates (Figure 11e). For 2 T, some small fragments of CNT aggregates in co-existence with the hook-like aggregates are seen (Figure 11f).

consisting of 50 wt.% TX-100 in water as a function of magnetic field and temperature has shown that the system exhibits hexagonal and isotropic phases on heating. For all the applied magnetic fields, the temperature dependence of electrical conductivity of the carbon nanotubes dispersed lyotropic liquid crystal system exhibited a discontinuous change at the hexagonal to isotropic transition temperature. They found that the magnetic field dependence of the hexagonal to isotropic transition temperature is similar to that of the viscosity of the system. Using photo images of the sample, they showed that the carbon nanotubes in the lyotropic liquid crystal, form magnetic field dependent aggregates and found spherical, rod and hook-like nanotube aggregates for low and high applied magnetic fields respectively. These nanotube aggregates were found to alter the viscosity of the system, which in turn alters the transition temperatures.
[Vijayaraghavan D., Jai Mishra and R. Thejas]

Liquid crystals – phenomenological theory

Stability and energetics of wall defects on spherical, ordered fluid membranes

The work on "Interplay between elasticity and topological defects on orientationally ordered, minimal-surface configurations of fluid membranes" undertaken by Saichand C., Jayakumar A., Arun Roy and Yashodhan Hatwalne has been converted into the study of the stability of topological defects on spherical, ordered fluid membranes. A manuscript on this work is currently under preparation.
[C. Saichand, Jaya Kumar A. (Indian Institute of Science, Bangalore), Arun Roy and Yashodhan Hatwalne]

Morphology of polymer crystallites

The long-term research programme of Yashodhan Hatwalne and collaborators Jayakumar A. and M. Muthukumar on constructing a unified phenomenological theory that accounts for the stability of all the observed structures of polymer crysttalites is nearing completion.
[Jaya Kumar A. (Indian Institute of Science, Bangalore), M. Muthukumar (University of Massachusetts, USA) and Yashodhan Hatwalne]

Topological instabilities in lyotropic smectic-A liquid crystals

Work on lyotropic smectic-A liquid crystals under compression by Yahodhan Hatwalne and collaborators Jayakumar A. and Rahul Pandit is motivated by the observed structure of the rough endoplasmic reticular in biological cells. During the past year, they have improved upon earlier work, and found a better method to obtain the full "phase diagram" of the different possible structures in parameter space.
[Jayakumar A. (IISc, Bangalore), Rahul Pandit (IISc, Bangalore) 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 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 SCM members Subhransu Dhar, Sebanti Chattopadhyay and Sayantan Majumdar. 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. By analyzing the asymptotic behaviour of viscosity below and above the shear-thickening onset for different packing fractions, they have shown that the signatures of shear-jamming can even be obtained from steady state measurements. In the shear jammed regime, in-situ optical images showed fracture and failure of the sample, reconfirming the formation of solid-like jammed state under shear.

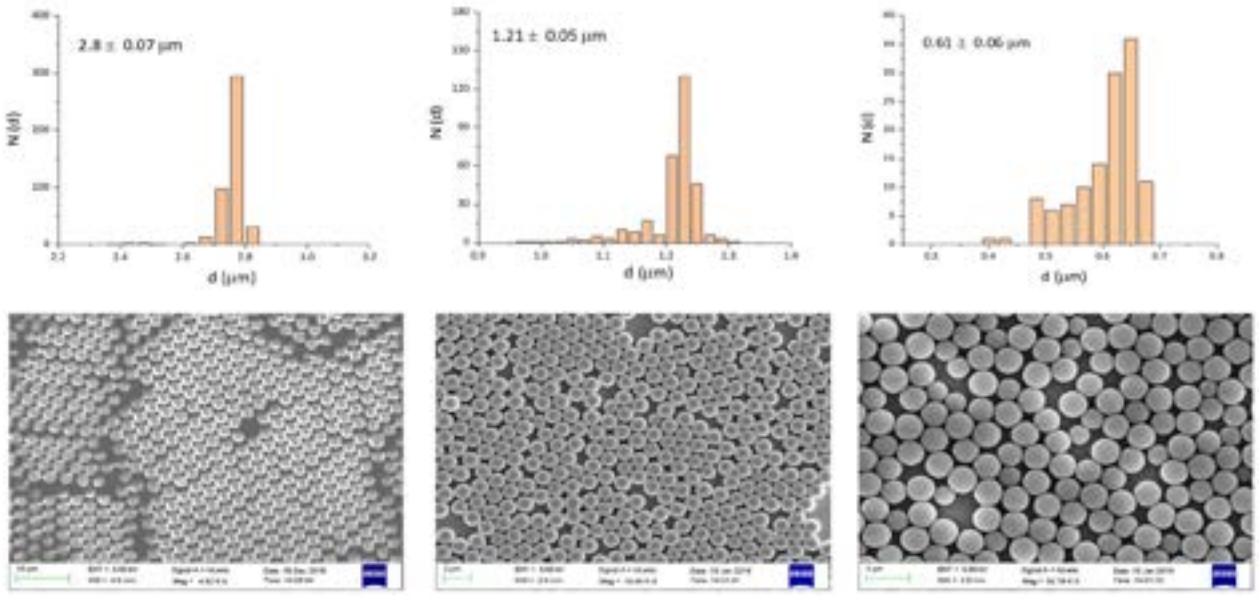


Figure 12. Monodisperse colloidal particles synthesized in the lab. Size range of 0.6 to 2.8 microns are shown.

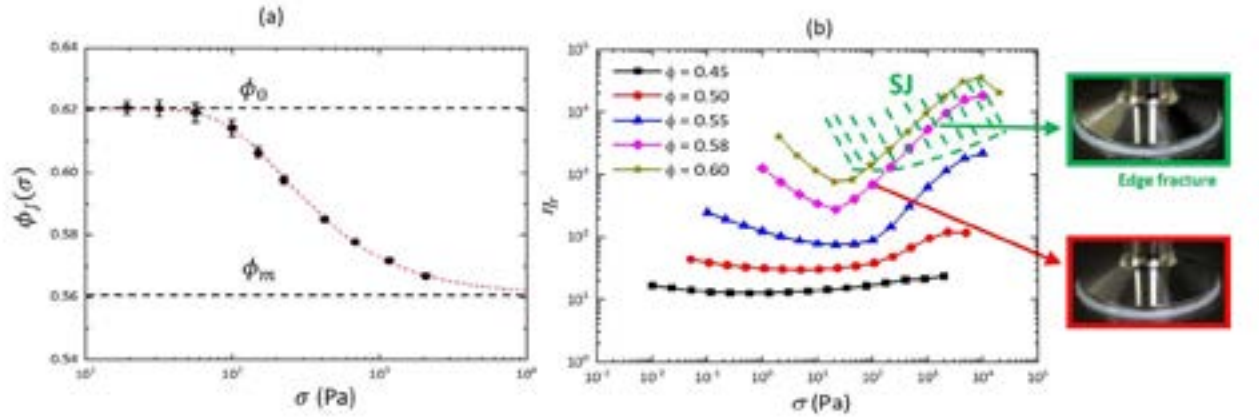


Figure 13. (a) Stress dependent jamming point obtained from asymptotic viscosity divergence. The dotted line is the fit to Wyart-Cates model. (b) Relative viscosity as a function of stress for different packing fractions of particles. The shear jammed phase (SJ) is concluded from (a) and shown in green. Optical image shows edge fracture of the sample for SJ, as indicated. The sample is 1.2 microns polystyrene microspheres in a solution of PEG-400, for both (a) and (b).

[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 (σ_y) but transforms into a liquid above σ_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 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 ($0.0001 < \gamma_0 < 1$) 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 γ_0, they found that the normalized dissipated energy shows a non-monotonic behaviour: it goes through a minimum at an intermediate γ_0 and saturates at a maximum value for larger values γ_0 , 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. The system displayed persistent shear banding over the entire range of strain variation. The width of the shear band remained almost independent of strain amplitude till the intermediate values of, but in the fluidized region the width of the band increases rapidly with γ_0. These experiments present a robust method to capture the yielding transition for highly non-linear systems.
[Sebanti Chattopadhyay and Sayantan Majumdar]

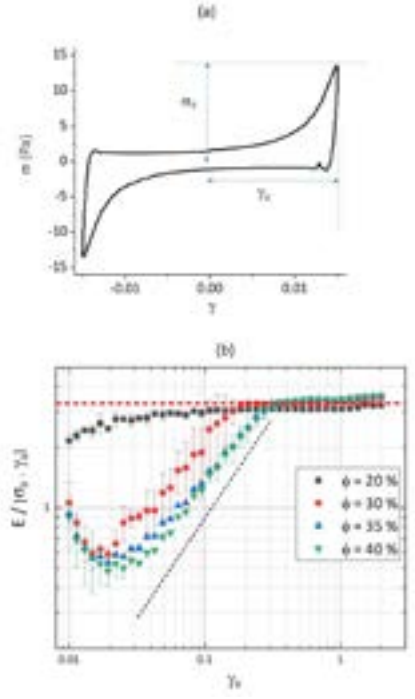


Figure 14. (a) Highly non-linear intra-cycle stress vs strain (Lissajous plot) for a yield stress fluid formed by fractal aggregates of cornstarch particles in paraffin oil obtained from oscillatory strain deformations. (b) Normalized energy dissipation as a function of applied strain amplitude for different volume fraction ϕ. Yield stress appears for $\phi > 25\%$. 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.

Strain softening and stiffening responses of spider silk fibres 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

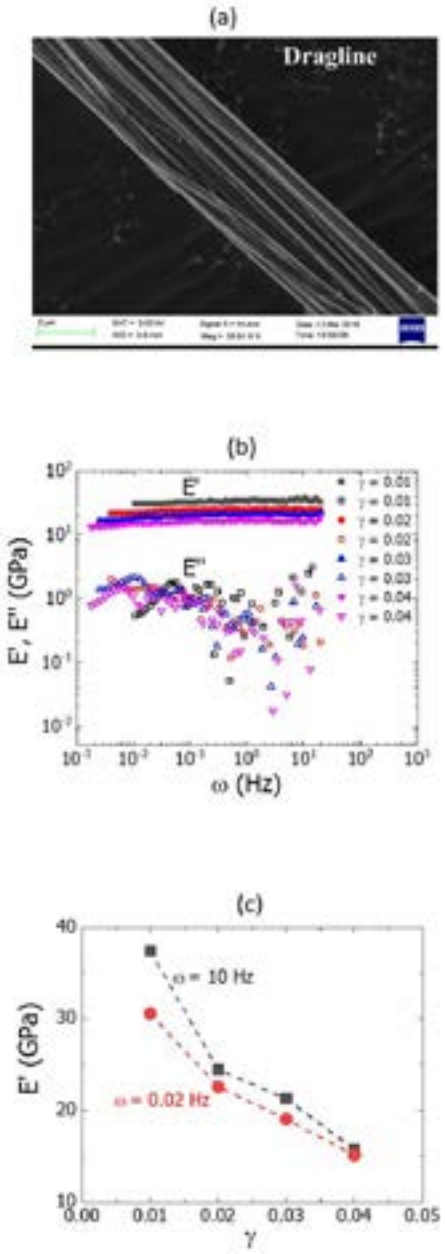


Figure 15. SEM image of a single dragline silk fibre composed of many micro-filaments. (b) Frequency dependent elastic (E') and viscous (E") extensional moduli of a single dragline fibre for different applied strain values obtained from the time domain stress relaxation data (c) Softening of fibre with increasing strain magnitude shown for two different frequencies.

strongest biomaterials 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 fibres, such characterization does not take into account the steady state mechanical behaviour and frequency response for a single silk fibre.

Ongoing projects and recent findings:

Sayantan Majumdar and collaborators 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 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 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. Additionally, they have also shown that silk stiffens while ageing within the typical lifetime of a web and suggest a possible mechanism for the observed non-linear response.
[Sushil Dubey, Chinmay Hemant Joshi (Indian Institute of Science Education and Research, Thiruvananthapuram), Sukh Veer, Hema Somanathan (Indian Institute of Science Education and Research, Thiruvananthapuram), Sayantan Majumdar and Pramod A Pullarkat]

Statistical similarities between earthquakes and flow of soft materials below yield stress

Earthquake, complex reorganization of earth crust caused mainly by the sudden release in energy from the fracture of geological faults is probably the most common natural phenomenon that adversely affects human lives. To cut through the complexity of such a large-scale reorganization phenomenon, there have been significant recent efforts in mimicking earthquake in controlled laboratory experiments by studying the deformation and failure in various solid materials under external loads. In these experiments, the readout of the events is acoustic emission in the form of crackling noise caused by predominant irreversible deformations of the optically opaque solid samples with typical shear moduli ~ MPa or higher. All these experiments are performed with a very high sampling rate (~ 100KHz and above) whereas, seismic vibrations of engineering significance occur at frequencies from less than 0.2Hz to 20Hz. Despite these experimental studies, to our knowledge, there is no similar study on soft and disordered materials that show solid-like yield stress. Such study is important since the mesoscopic domain structures in this broad class of materials can be reversibly controlled by an applied shear stress or an external field. In general, similar tunability of domain structures is not accessible for conventional solids. The major challenge to study reorganization events in soft yield-stress materials originates from the fact that they are much softer (shear moduli few tens of Pa) compared to those used in experiments mentioned earlier. Materials with such low values of shear moduli do not produce audible crackling noise under stress and therefore, the statistical properties of reorganization events cannot be read out using acoustic emissions.

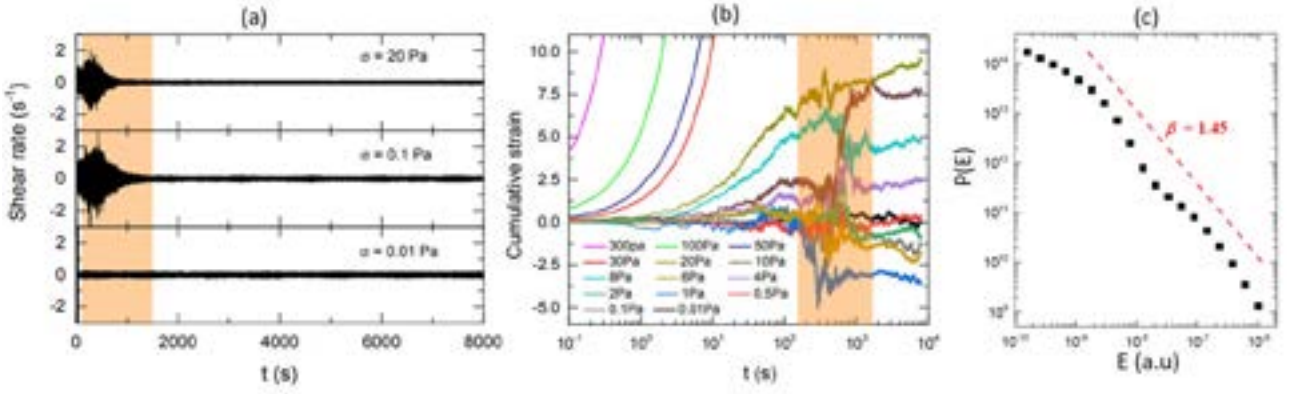


Figure 16. (a) Earthquake seismograph like burst events in shear rate fluctuations as a function of time for different applied Stress values below yield stress (~27 Pa). (b) Cumulative strain obtained from the time integration of the data in (a) for different stress values both below and above the yield stress. Below yielding, in the time window corresponding to shear rate Burst, sudden reorganizations happen in the system. (C) Distribution of kinetic energy of the shearing plate shows power-law behaviour, consistent with Gutenberg-Richter law for real earthquakes.

Ongoing projects and recent findings:

Shear stress-induced reorganization of yield stress solids formed by nematic phase of surfactant micelles and repulsive Wigner glass formed by laponite particles was studied during the past year by Sayantan Majumdar along with collaborators P. K. Bera, Guy Ouillion, Didier Sornette and A. K. Sood. These two systems have widely different microstructures. The creep response of these systems below the yield stress results in angular velocity fluctuations of the shearing plate that resembles seismograph data measuring the ground motion during earthquake avalanches, showing large temporal bust-like events. Remarkably, they found that the statistical properties of these burst-like events follow the well-known scaling relations for magnitude and frequency distribution of earthquakes, given by Gutenberg-Richter and Omori laws. Using shear rheology and in-situ polarized optical microscopy, they have shown that for small applied stress values below the yielding point, the system self organizes and makes a transition to a much stronger solid-like state. These experiments extend the scaling relations for earthquake avalanches in the broad realm of yield stress materials where the domain structures can be easily tuned in a reversible manner by applied stress or external fields. Furthermore, these structures can also be imaged for a better understanding of force induced complex reorganization dynamics in a wide range of materials.
[P. K. Bera (Indian Institute of Science, Bangalore), Sayantan Majumdar, Guy Ouillion (Lithophyse, 4 rue de l'Ancien Sénat, Nice, France), Didier Sornette (ETH Zürich, Zürich, Switzerland), A. K. Sood (Indian Institute of Science, Bangalore)]

Structure, dynamics and rheology of non-Newtonian fluid

Electric field induced gelation in aqueous Laponite suspensions

Aqueous colloidal LAPONITE® clay suspensions transform spontaneously to a soft solid-like arrested state as its aging or waiting time increases. Former RRI postdoctoral fellow Paramesh Gadige and SCM group member Ranjini Bandyopadhyay have during the past year reported the rapid transformation of aqueous LAPONITE® suspensions into soft solids due to the application of a DC electric field with substantial increase in the speed of solidification at higher electric field strengths. The electric field was applied across two parallel brass plates immersed in the LAPONITE® suspension. They attribute the subsequent solidification that takes place on the surface of the positive electrode to the dominant negative surface charges on the LAPONITE® particles and the associated electrokinetic phenomena. With increasing electric field strength, a dramatic increase was recorded in the elastic moduli of the samples. These electric field induced LAPONITE® soft solids demonstrated all the typical rheological characteristics of soft glassy materials. A two-step shear melting process similar to that observed in attractive soft glasses was observed in these samples. The microstructures of the samples, studied using cryo-scanning electron microscopy (SEM) are seen to consist of percolated network gel-like structures, with the connectivity of the gel network increasing with increasing electric field strengths. In comparison with salt induced gels, the electric field induced gels studied here are found to be mechanically stronger and more stable over longer periods of time.

Figure 17. The artwork, based on the content of the paper reporting this work (Soft Matter, 2018,14, 6974-6982), was selected for the inner back cover of the journal.
[Paramesh Gadige (Sathya Sai Institute of Higher Learning, Andhra Pradesh) and Ranjini Bandyopadhyay]

Temperature and stiffness induced phase changes in dense suspensions of thermoresponsive Poly(N-isopropylacrylamide) colloidal particles

The temperature and stiffness induced phase changes in dense suspensions of Poly(*N*-isopropylacrylamide) PNIPAM colloidal particles and their macroscopic mechanical responses in oscillatory strain sweep experiments was studied by Sanjay Behera, Rajkumar Biswas and Ranjini Bandyopadhyay. The stiffness of PNIPAM colloidal particles was controlled by varying the concentration of the crosslinkers in the one-pot

synthesis method. Dense suspensions of these particles showed a non- monotonic increase of viscoelastic moduli with increase in temperature. They observed that when the temperature is increased above the lowest critical solution temperature (LCST), the rigidity moduli of the suspensions increases with increasing temperature. While this observation is contrary to intuition, they successfully explained it by considering that the hydrophobicity of the particles increases with temperature. The increase in temperature above the LCST also affects the underlying microscopic structures of these suspensions. Above the LCST, a rheological investigation of suspensions of stiff particles showed a two- step yielding behaviour similar to that observed in attractive glasses, while suspensions of soft particles showed a distinct nonlinear viscoelastic behaviour with increasing strain amplitude unlike metastable complex fluids such as colloidal glasses and gels. Cryogenic scanning electron microscopy enabled direct visualization of the microscopic structures of dense suspensions of these particles of different stiffnesses at different temperatures leading to observation of a transition from a gel network to a structure constituted by attractive clusters in suspensions of stiff particles with increasing temperature. Suspensions of soft particles, however, were always seen to remain in the gel phase for the entire range of temperatures explored in these experiments.

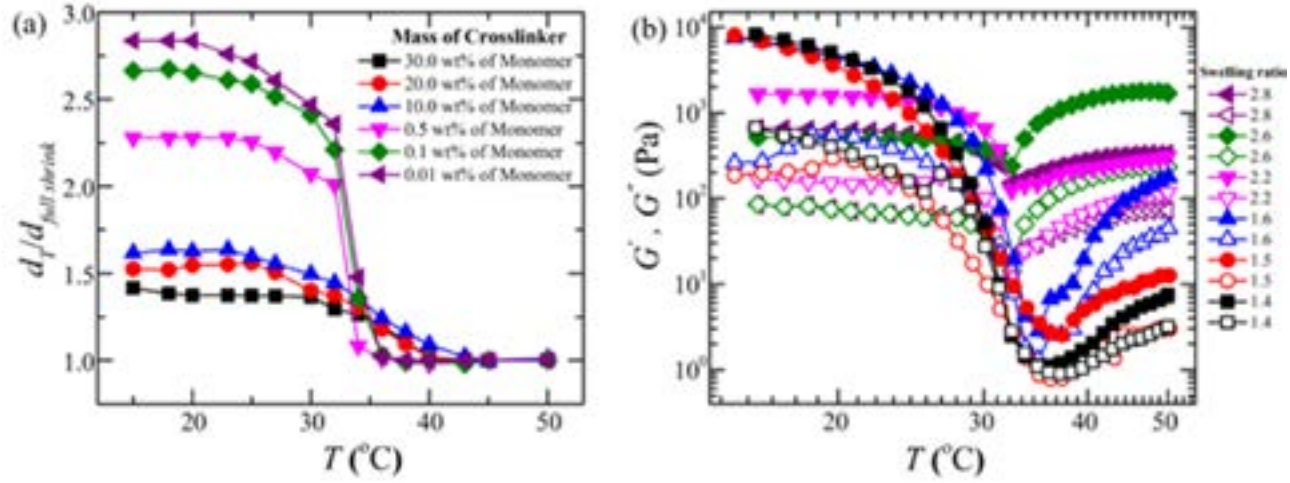


Figure 18. Temperature dependent swelling ratio *dT/dfull shrink* as a function of temperature *T* for suspensions of PNIPAM particles synthesized by varying the concentrations of crosslinker. (b) Temperature dependent linear elastic modulus G' (solid symbols) and viscous modulus G" (open symbols) of suspensions of PNIPAM particles of different swelling ratios.

[Sanjay Behera, Rajkumar Biswas and Ranjini Bandyopadhyay]

Physics of Lipid Membranes and Polyelectrolytes

Electrostatic interaction in strong electrolytes

Electrostatic interaction between two charged surfaces in a dilute electrolyte is well described by the Debye Huckel theory. However, recent experiments probing these interactions in strong electrolytes have uncovered surprising deviations from the predictions of this theory. It was found that on increasing the ionic strength the Debye length, which characterizes the decay of the electric potential away from the charged surface, first decreases reaching a minimum and then starts to increase. The increasing trend of the Debye length at high ionic strengths is very puzzling and is not accounted for by any theory. In order to check the universality of these results, Meera Thomas, Anindya Chowdhury and V. A. Raghunathan have studied the interaction of charged lipid membranes, which are flexible charged surfaces, dispersed in an aqueous solution as a function of salt concentration. The preliminary results confirm the re-emergence of the electrostatic repulsion at very high salt concentrations. Further experiments are underway to understand the factors responsible for this behaviour.

[Meera Thomas, Anindya Chowdhury and V. A. Raghunathan]

Interaction of acetic acid with lipid membranes

Studies of the interaction of uridine monophosphate (UMP) with phosphatidylcholine (PC) lipid membranes by Sreeja Sasidharan and V. A. Raghunathan has shown that UMP molecules bind to the membrane and increase its fluidity. The binding of the charged UMP molecules

also led to a long-range electrostatic repulsion between the membranes resulting in the formation of unilamellar vesicles in dilute solutions. On incubating the system over a few days, a phase consisting of interdigitated bilayers was found to form, which on heating transformed into an inverted hexagonal phase. Surprisingly an almost identical behaviour was observed when UMP was replaced with acetic acid. Further, acetic acid was found to create pores in fluid bilayers. They further show that this property can be exploited for the preparation of supported lipid bilayers, which are widely used models for cell membranes. This protocol is much simpler and faster than those available in the literature. They are currently investigating the interactions between these small molecules and the lipid membrane responsible for the observed behaviour.
[Sreeja Sasidharan and V. A. Raghunathan]

Biophysics

Biophysics of Axons

Introduction

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 pose 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 that 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 that 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.

Members of the biophysics lab at RRI aim to investigate the mechanical and dynamical properties of the axonal membrane-cytoskeleton complex. For this they have developed an optical fibre based Micro-Extension Rheometer to probe mechanical responses of axons and use optical tweezers to study axonal membrane properties.

Research work undertaken during 2018-19 is sumarised 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, which can now operate in a constant-strain mode. By combining this technique with biochemical and genetic modifications to neuronal cells, he has shown that cortical actin and spectrin—a long multidomain protein—are major components in defining the non-linear viscoelasticity of axons. The results demonstrate for the first time that axons exhibit reversible strain softening, and a non-monotonous variation of relaxation time as a function of strain. In addition, super resolution imaging revealed a periodic actin-spectrin skeleton. Theoretical modelling of the elastic response of such a structure showed that the observed responses can be well explained by considering the stochastic, reversible, unfolding-refolding dynamics of spectrin domains under applied force. The relaxation time behaviour arises from the force dependence of the

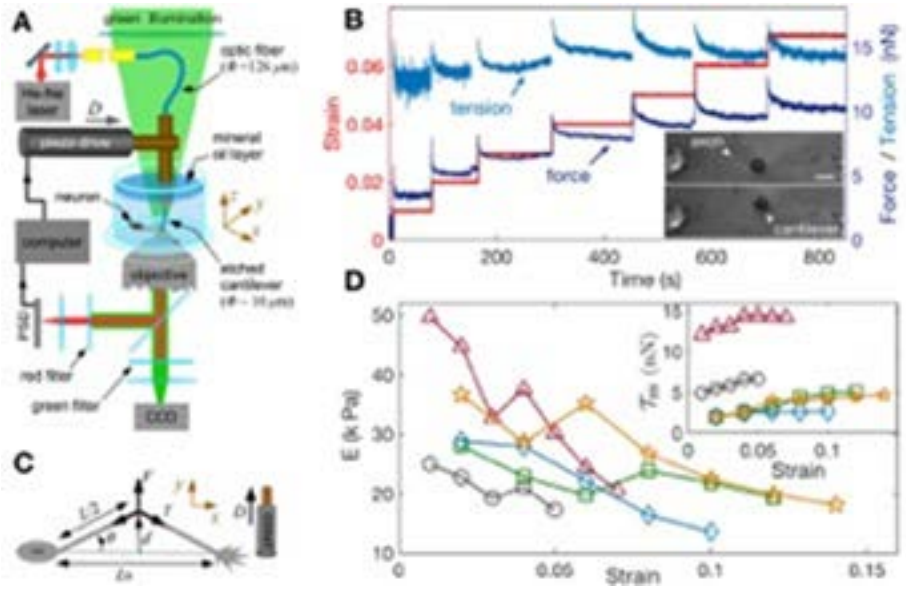


Figure 19. (A) A schematic of the Micro-Extension Rheometer developed at RRI, which uses an etched optical fibre as cantilever and a computer feedback loop to operate in constant strain mode. (B) Plots of the applied strain steps, corresponding measured force and calculated tension. The inset shows images 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 saturates with increasing strain.
[Sushil Dubey, Nishita Bhember, Aurnab Ghose (IISER-Pune), Serene Rose David, Andrew Callan Jones (University-Paris, France) and Pramod Pullarkat]

unfolding and refolding rates as the axon is stretched. These results showed that the actin-spectrin structure acts as a tension buffer or a shock absorber in the axon. This work, under revision with additional experiments, is available on bioRxiv.

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

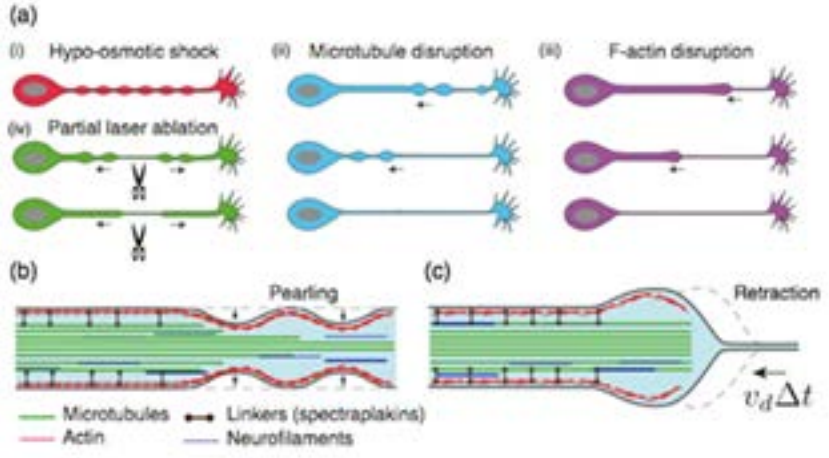


Figure 20. Schematic diagrams showing the variety of shape instabilities exhibited by axons under different perturbations.

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. Alka 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 have shown that these shape changes can be induced by breakages in the cytoskeleton. Performing such experiments in presence of a microtubule stabilising agent shows 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. Additional experiments were performed to probe the effect of the periodic actin-spectrin lattice of the axon. The results were communicated for publication (available at bioRxiv).
[Anagha Datar, Jaisha Bhanu, Roli Srivastava, Alka Bhat, Roberto Bernal (University of Santiago, Chile), Jacques Prost (Institute Curie, Paris), Andrew Callan-Jones

(Institute Curie, Paris) and Pramod Pullarkat]

Cell adhesion studied using a home-developed shear device

Renu Vishavkarma and Pramod Pullarkat had developed a shear device for studying the effect of shear stress on cells along with fluorescence microscopy. The device itself is new—it was made using a computer hard-disk motor that provides superb wobble-free performance and is very compact and hence mountable on any standard microscope including confocal systems. Renu had shown that this device can differentiate changes in adhesion and it can also be used along with micro-patterning to create well defined cell geometries. She had shown that cell adhesion could be quantitatively studied by measuring the cell detachment under either a constant shear as a function of time or as a function of shear stress. Motivated by this, a theoretical model was developed in collaboration with collaborator Gautam Menon where cell adhesion bonds stochastically bind and unbind in a force dependent manner. This model accounts for all the experimental observations and highlights the importance of quantifying cell spread area in obtaining the correct description of cell adhesion. This article is now published in Physical Biology.

Subsequently, Ashish Mishra has taken up this project and he has made significant improvements to the technique by adding home-made electronics which enable computer control and maintenance of a constant RPM for the motor irrespective of load, and temperature control. Ashish has also developed micro-patterning techniques and is now in a position to conduct new experiments. This is a collaborative effort with Namrata Gundiah and Gautam Menon and they have now secured a joint grant from DBT for continuing this project.
[Renu Vishavkarma, Ashish Mishra, Namrata Gundiah (IISc, Bangalore), Gautam Menon (IMSc, Chennai) and Pramod Pullarkat]

Membrane tether mechanics

Susav Pradan had conducted a series of experiments showing that membrane tethers pulled out of axons of neuronal cells can be used as model systems to study filopodial dynamics. Filopodia are tube like extensions generated by motile cells utilising polymerisation forces generated by actin bundles. The mechanism for filopodial dynamics— growth, contractility and retraction—is not well understood. This model system exhibits all major filopodia-like dynamics and is conducive to quantitative measurements of forces. Susav, along with Arsalan Mohammad Ashraf performed several more experiments to conclusively rule out the role of myosin-II motors in force generation. In collaboration with Jacques Prost, current efforts are towards developing a model for a possible novel mechanism where twisting of actin filaments by actin-binding-proteins may be responsible for the contractile response. This is being tested experimentally by Arsalan using new molecular biology tools like GFP proteins developed by Serene Rose David.

Susav had also done a series of experiments to measure cell membrane tension as part of collaboration with the lab of Satyajit Mayor at NCBS, Bangalore. This work is now published in Nature Communications, 2018.
[Susav Pradhan, Arsalan Mohammad Ashraf, Serene Rose David, Jacques Prost (Institute Curie, Paris) and Pramod Pullarkat]

Nanoscale biophysics of biological systems

The research interests of the 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 2018-19, two distinct single molecule methodologies to look into single DNA mechanics were developed:

Laser Optical Tweezers (LOT) based manipulation of single DNA molecules

Durai Murugan Kandaswamy, Intezar Husain, Mahesh B. L. and Gautam Soni have developed a home-built optical tweezers system capable of manipulating single DNA molecules. Figure 21 below shows the current state of the optical tweezers system. Figure 21A and B shows the schematic and image of the custom-built optical system. Figure C shows the XY position (in nm) of an optically trapped bead as registered by a quadrant photo detector. Figures 21D and E shows stiffness calibration of the optical trap, measured at different laser power. Figure 21D uses the equipartition theorem and Figure 21E uses the power spectral density (PSD) of thermal fluctuations of trapped bead. Figure 21F shows the linear dependence of spring constant, k_{trap}, of the trap, as calculated by the PSD method, on the laser power. This system will be used for measuring mechanical properties of DNA molecules when interacting with different DNA binding proteins. This setup will also be used for measuring the structural interactions that underlie chromatin function in biological systems.

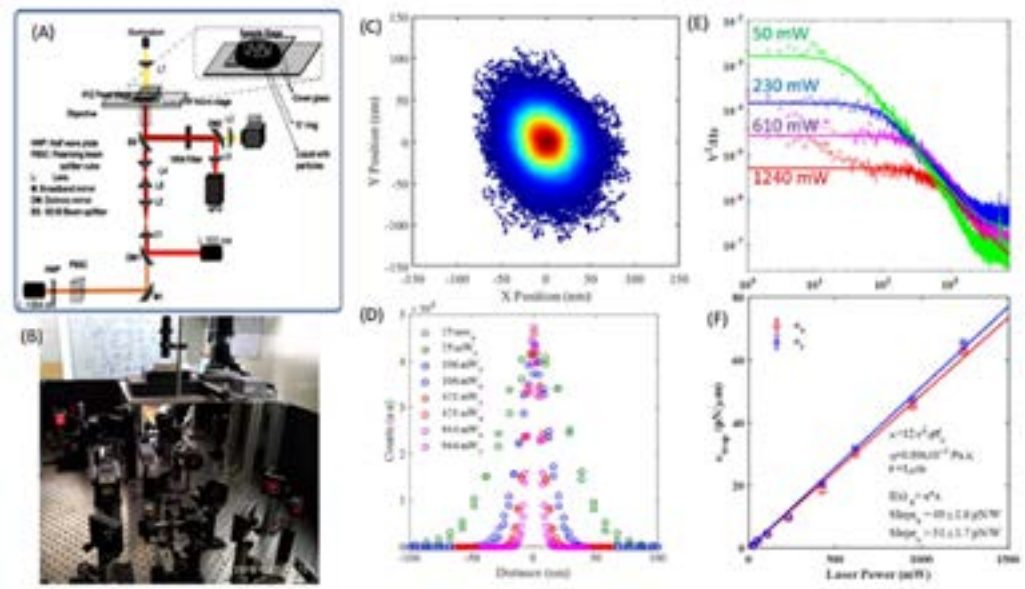


Figure 21. A custom built Laser Optical Tweezers (LOT) system
[Durai Murugan Kandaswamy, Intezar Husain, Mahesh B. L. and Gautam Soni]

Nanopore Platform based Screening (NPS) of single DNA molecules

Sumanth Kumar, Saurabh Koushik, Koushik S., Kousik Bera, Divya S., Serene R. D. and Gautam Soni have further developed the home built nanopore platform for DNA screening. Figure 24 below shows the current status of the nanopore system. They have successfully fabricated nanopores in the range of 5nm to 5000nm. Figure 22A (i) shows typical images as well as I-V curves for glass (quartz) nanopores of different diameters. (ii) shows open pore conductance before and after adding DNA to the nanopore cis chamber. After adding DNA, single DNA molecules are detected translocating through the nanopore in the form of electrical blockade events. Figure 22B shows a variety of DNA polymer configurations as it translocates through the pore. All polymer configurations are uniquely identified in the nanopore system. The histogram on the right shows translocation events corresponding to 1,2,3... and so on number of DNA molecules detected using the nanopore. Figure 22C shows the typical conductance blockades (dG) & dwell time (dt) histograms of about 1000 DNA molecules passing through the nanopore. The dG-dt scatter plot is shown to visually contrast configurational population of DNA molecules translocating through 20 nm glass nanopores.

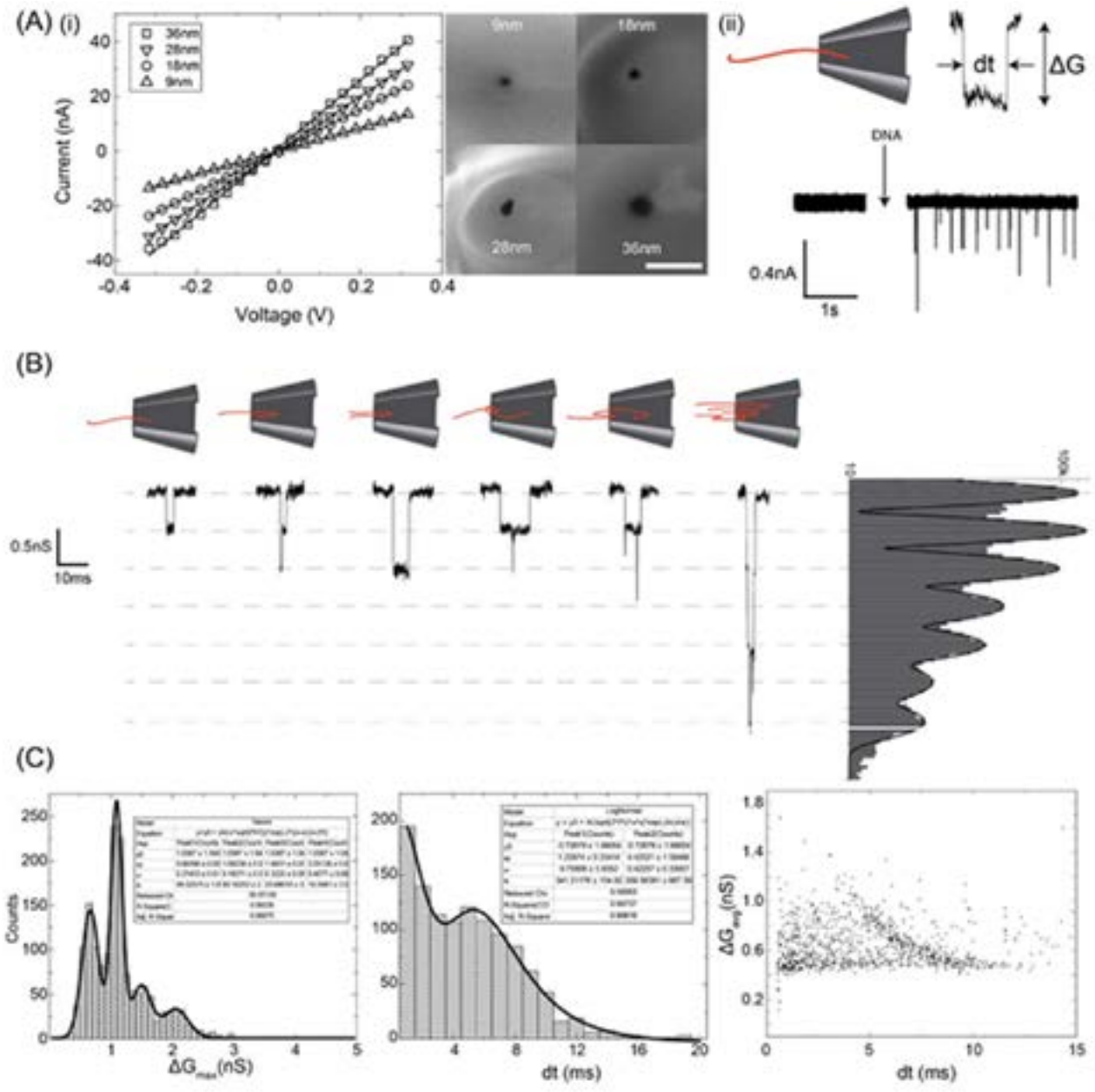
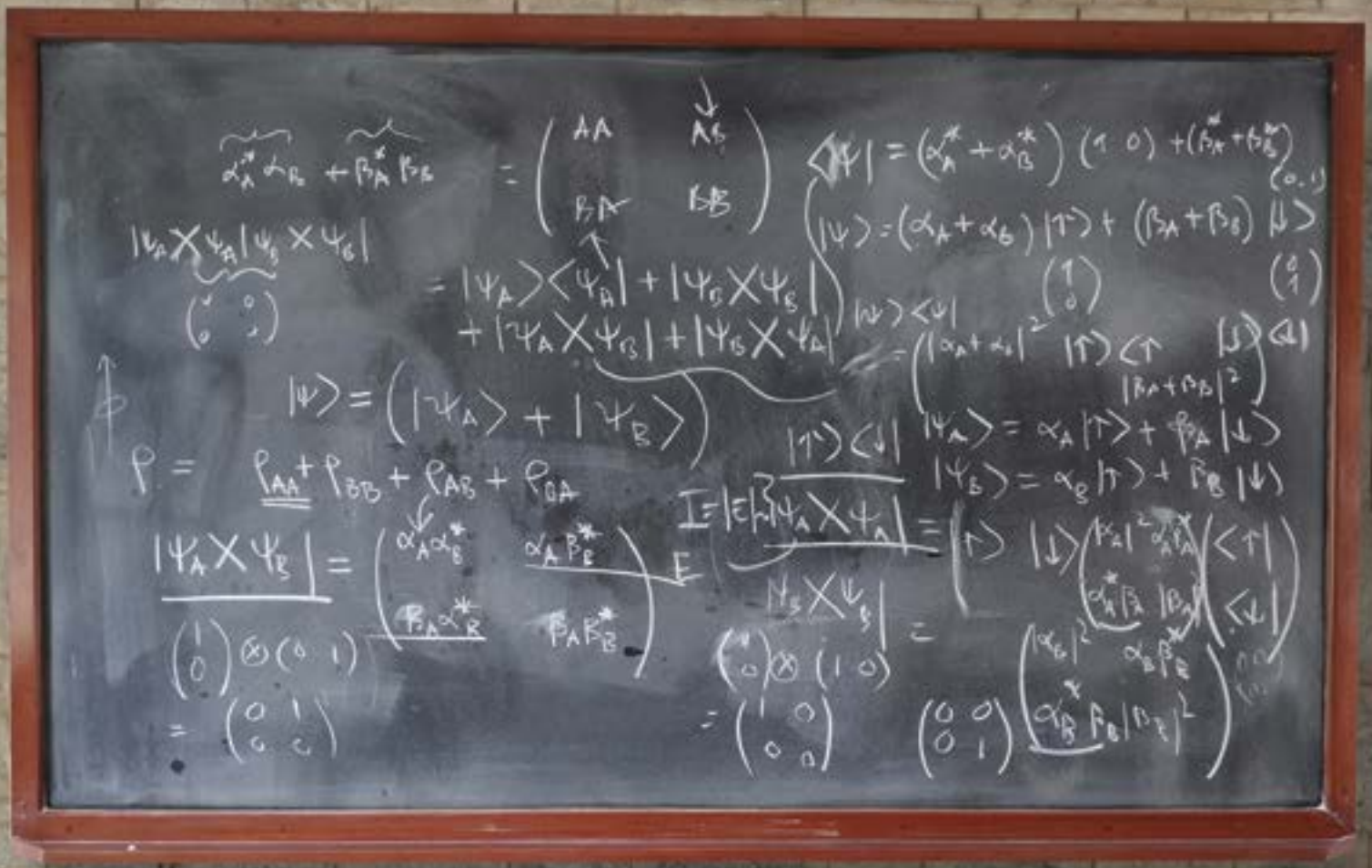


Figure 22. Nanopore Platform for Screening (NPS) of biomolecules.
[Sumanth Kumar, Saurabh Koushik, Koushik S., Kousik Bera, Divya S., Serene R. D. and Gautam Soni]

Research efforts in the lab is also towards understanding force transduction across the cell nucleus. Saurabh Kaushik, Manohar M. and Gautam Soni are addressing this problem at the cell nucleus by isolating the mechanical transducers across the cell nucleus and studying their mechanical properties.
[Saurabh Kaushik, Manohar M. and Gautam Soni]



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 2018-19

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.

Statistical physics gives a probabilistic description of systems that evolve in a stochastic manner. Examples of such systems include the motion of colloidal particles in water, motion of bacteria, externally shaken granular particles, as well as gas in equilibrium. For equilibrium systems, there is a well-defined formalism to study the static properties. However, for systems away from equilibrium, there is no standard method. During the past year, Sanjib Sabhapandit and his students at RRI along with collaborators, investigated such nonequilibrium systems using various mathematical methods.

Run-and-tumble particle in one-dimensional confining potential: Steady state, relaxation and first passage properties

Sanjib Sabhapandit and collaborators Abhishek Dhar, Anupam Kundu, Satya N. Majumdar, and Gregory Schehr studied the dynamics of a one-dimensional run and tumble particle subjected to confining potentials of the type $V(x) = \alpha\ |x|^p$, with $p > 0$. The noise that drives the particle dynamics is telegraphic and alternates between ± 1 values. They have shown that the stationary probability density $P(x)$ has a rich behavior in the (p,α)-plane. For $p > 1$, the distribution was found to have a finite support in $[x_-,x_+]$ and there is a critical line $\alpha_c(p)$ that separates an active-like phase for $\alpha > \alpha_c(p)$ where $P(x)$ diverges at $x_\pm$, from a passive-like phase for $\alpha < \alpha_c(p)$ where $P(x)$ vanishes at $x_\pm$. For $p < 1$, the stationary density $P(x)$ collapses to a delta function at the origin, $P(x) = \delta(x)$. In the marginal case $p = 1$, they have shown that, for $\alpha < \alpha_c$, the stationary density $P(x)$ is a symmetric exponential, while for $\alpha > \alpha_c$, it again is a delta function $P(x) = \delta(x)$. For the harmonic case $p = 2$, they have obtained exactly the full time-dependent distribution $P(x,t)$, that allowed them to study how the system relaxes to its stationary state. In addition, for this $p = 2$ case, they have also studied analytically the full distribution of the first-passage time to the origin. Numerical simulations were found to be in complete agreement with their analytical predictions. This work has been published in Phys. Rev. E 99, 032132 (2019).
[Abhishek Dhar (ICTS, Bangalore), Anupam Kundu (ICTS, Bangalore), Satya N. Majumdar (LPTMS, CNRS, Univ. Paris-Sud, Universite Paris-Saclay, Orsay, France))], Sanjib Sabhapandit, and Grégory Schehr (LPTMS, CNRS, Univ. Paris-Sud, Universite Paris-Saclay, Orsay, France)]

Statistics of overtake events by a tagged agent

Sanjib Sabhapandit and Santanu Das along with collaborator Deepak Dhar considered a minimalist model of overtaking dynamics in one dimension. They considered that on each site of a one-dimensional infinite lattice sits an agent carrying a random number specifying the agent's preferred velocity, which is drawn initially for each agent independently from a common distribution. The time evolution is Markovian, where a pair of agents at adjacent sites exchange their positions with a specified rate, while retaining their respective preferred velocities, only if the preferred velocity of the agent on the "left" site is higher. Using this model, they discussed two different cases: one in which a pair of agents at sites i and $i + 1$ exchange their positions with rate 1, independent of their velocity difference, and another in which a pair exchange their positions with a rate equal to the modulus of the velocity

difference. In both cases, they found that the net number of overtake events by a tagged agent in a given duration t, denoted by $m(t)$, increases linearly with time t, for large t. In the first case, for a randomly picked agent, m/t, in the limit $t \to \infty$, was distributed uniformly on $[-1, 1]$, independent of the distributions of preferred velocities. In the second case, the distribution was given by the distribution of the preferred velocities itself, with a Galilean shift by the mean velocity. They also found the large time approach to the limiting forms and compared the results with numerical simulations. This work has been published in Phys. Rev. E 98, 052122 (2018).
[Santanu Das, Deepak Dhar (IISER, Pune), and Sanjib Sabhapandit]

Velocity distribution of driven granular gases

The granular gas is a paradigm for understanding the effects of inelastic interactions in granular materials. Kinetic theory provides a general theoretical framework for describing the granular gas. Its central result is that the tail of the velocity distribution of a driven granular gas is a stretched exponential that, counterintuitively, decays slower than that of the corresponding elastic gas in equilibrium. However, a derivation of this result starting from a microscopic model is lacking. During 2018-19, Sanjib Sabhapandit and collaborators V. V. Prasad, Dibyendu Das, and R. Rajesh have obtained analytical results for a microscopic model for a granular gas where particles with two-dimensional velocities are driven homogeneously and isotropically by reducing the velocities by a factor and adding a stochastic noise. They found two universal regimes: For generic physically relevant driving, it was found that the tail of the velocity distribution is a Gaussian with additional logarithmic corrections. Thus, the velocity distribution decays faster than the corresponding equilibrium gas. The second universal regime was found to be less generic and corresponds to the scenario described by kinetic theory. Here, the velocity distribution was shown to decay as an exponential with additional logarithmic corrections, in contradiction to the predictions of the phenomenological kinetic theory, necessitating a re-examination of its basic assumptions. A publication on this work is accepted and will appear in J. Stat. Mech (2019).
[V. V. Prasad (Weizmann Institute of Science, Israel, The Institute of Mathematical Sciences, Chennai, Homi Bhabha National Institute, Mumbai), Dibyendu Das (IIT, Mumbai), Sanjib Sabhapandit and R. Rajesh (The Institute of Mathematical Sciences, Chennai, Homi Bhabha National Institute, Mumbai)]

Non-equilibrium Quantum Langevin dynamics of orbital diamagnetic moment

The time dependent orbital diamagnetic moment of a charged particle in a magnetic field in a viscous medium was investigated via the Quantum Langevin Equation by Urbashi Satpathi and Supurna Sinha. The study focused on the interplay between the cyclotron frequency and the viscous damping rate and its effect on the dynamics of the orbital magnetic moment in the high temperature classical domain and the low temperature quantum domain for an Ohmic bath. These predictions can be tested via state of the art cold atom experiments with hybrid traps for ions and neutral atoms. The effect of a confining potential on the dynamics of the magnetic moment was also studied and the expected Bohr Van Leeuwen limit was obtained in the high temperature, asymptotic time ($\gamma t \longrightarrow \infty$, where γ is the viscous damping coefficient) limit. This work has been published in Journal of Statistical Mechanics: Theory and Experiment (J. Stat. Mech. (2019) 063106)
[Urbashi Satpathi (Formerly a Postdoctoral fellow at RRI, currently at ICTS, Bangalore) and Supurna Sinha]

Active Brownian Motion in Two-dimensions

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. During the past year, Urna Basu along with collaborators Satya N. Majumdar, Alberto Rosso and Gregory Schehr have studied one of the simple models of active particles, namely, the active Brownian particle (ABP) in two spatial dimensions. ABP describes the motion of an overdamped particle with a constant speed but its orientation undergoes a rotational diffusion. Consequently, the ABP has an intrinsic timescale D_R^{-1} set by the rotational diffusion constant D_R. They have shown that, at short times $t \ll D_R^{-1}$, the presence of activeness results in a strongly anisotropic and nondiffusive dynamics in the (xy) plane. They computed exactly the marginal distributions of the x and y position coordinates along with the radial distribution, which were all shown to be non-Brownian. In addition, it was shown that, at early times, the ABP has anomalous first-passage properties, characterized by non-Brownian exponents.
[Urna Basu and collaborators Satya N. Majumdar, Alberto Rosso and Gregory Schehr from LPTMS, Univ. Paris-Sud, France]

Symmetric Exclusion Process under 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. The paradigmatic example is that of a Brownian motion under resetting, where the position of the particle is reset to a fixed point in space with a certain rate. Various extensions and generalizations of this model have been studied in the literature, but almost all of these concern systems with single or few degrees of freedom. Recently, Urna Basu along with collaborators Anupam Kundu and Arnab Pal has explored the question: how does stochastic resetting affect the dynamical behaviour of an interacting many particle system? Studies of the behaviour of a Symmetric Exclusion Process (SEP) in presence of stochastic resetting where the configuration of the system is reset to a step-like profile with a fixed rate r showed that the presence of resetting affects both the stationary and dynamical properties of SEP strongly. They computed the exact time-dependent density profile and showed that the stationary state is characterized by a non-trivial inhomogeneous profile in contrast to the flat one for $r = 0$. They have also shown that for $r > 0$ the average diffusive current grows linearly with time t, in stark contrast to the t growth for $r = 0$. In addition to the underlying diffusive current, they have identified the resetting current in the system which emerges due to the sudden relocation of the particles to the step-like configuration and have computed the probability distributions of the diffusive current and the total current (comprising of the diffusive and the resetting current) using the renewal approach. Finally, they have demonstrated that while the typical fluctuations of the diffusive current around the mean are typically Gaussian, the distribution of the total current shows a strongly non-Gaussian behaviour. [Urna Basu, Anupam Kundu (ICTS, India) and Arnab Pal (Tel-Aviv University, Israel)]

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.

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').

From Euclidean to Lorentzian Loop Quantum Gravity via a Positive Complexifier

Overview:

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. The classical dynamics of the theory is controlled by a Hamiltonian called the Hamiltonian constraint. It turns out that in LQG it is expected to be significantly simpler to attempt a construction of the Hamiltonian constraint operator for the case of Euclidean General. Relativity (which describes a dynamical theory of 4d spatial geometry) than to do so for the physically relevant case of Lorentzian General Relativity (which describes the dynamics of 4d space time). In the early days of LQG, Thiemann proposed that dynamical solutions of Lorentzian LQG could be obtained by a 'Wick' transformation of those of Euclidean LQG. This transformation is generated by a certain Wick rotation operator.

During the past year, Madhavan Varadarajan re-considered Thiemann's proposal in the light of subsequent developments, introduced and advocated the use of a new positive Wick rotator and suggested a quantum Hilbert Space arena for its definition. Since his recent work on the Hamiltonian constraint suggests avenue for progress in Euclidean LQG, this work, in turn re-examines how such progress in the Euclidean theory could directly feed into the definition of Lorentzian LQG.

Details:

Madhavan constructed a positive complexifier, differentiable almost everywhere on the classical phase space of real triads and SU(2) connections, which generates a Wick Transform from Euclidean to Lorentzian gravity everywhere except on a phase space set of measure zero.

This Wick transform assigns an equal role to the self dual and anti-self dual Ashtekar variables in quantum theory. He argued that the appropriate quantum arena for an analysis of the properties of the Wick rotation is the diffeomorphism invariant Hilbert space of Loop Quantum Gravity (LQG) rather than its kinematic Hilbert space and examined issues related to the construction, in quantum theory, of the positive complexifier as a positive operator on this diffeomorphism invariant Hilbert space. Assuming the existence of such an operator, he explored the possibility of identifying physical states in Lorentzian LQG as Wick rotated images of physical states in the Euclidean theory. His considerations are derived from Thiemann's remarkable proposal to define Lorentzian LQG from Euclidean LQG via the implementation in quantum theory of a phase space 'Wick rotation' which maps real Ashtekar-Barbero variables to Ashtekar's complex, self dual variables. This work is now published as an article titled "From Euclidean to Lorentzian Loop Quantum Gravity via a Positive Complexifier."
[Madhavan Varadarajan]

On quantum propagation in Smolin's weak coupling limit of 4d Euclidean Gravity

Overview:

Due to an influential paper by Smolin in the 90's, a folklore has developed in the field that quantum dynamics in LQG constructions are not consistent with the propagation of perturbations. A quantum dynamics, which does not propagate perturbations is unlikely to reproduce General Relativity in a classical limit because the latter theory does display propagating excitations such as gravitational waves. Within the simple context of a 2d field theory, Madhavan Varadarajan showed a few years ago that this folklore is wrong and that LQG constructions there can lead to propagating dynamics. The model studied, however, was vastly simpler than gravity and it is desirable that a demonstration of propagation be available for more complex systems closer to gravity.

In this regard, Madhavan's current work demonstrates that LQG methods applied to the immensely more complex system of weakly coupled Euclidean Gravity can result in propagation. The system studied has many of the complexities of gravity and the structures responsible for propagation seem sufficiently robust as to play a role in full blown Euclidean gravity. This work together with his earlier work on a consistent quantum dynamics for this weak coupling model sets the stage for tackling Euclidean LQG. The work above (From Euclidean to Lorentzian Loop Quantum Gravity via a Positive Complexifier) then suggests a road map to the Lorentzian theory.

Details:

Two desirable properties of a quantum dynamics for Loop Quantum Gravity (LQG) are that its generators provide an anomaly free representation of the classical constraint algebra and that physical states which lie in the kernel of these generators encode propagation. A physical state in LQG is expected to be a sum over graphical SU(2) spin network states. By propagation it is meant that a quantum perturbation at one vertex of a spin network state propagates to vertices which are 'many links away' thus yielding a new spin network state which is related to the old one by this propagation. A physical state encodes propagation if its spin network summands are related by propagation. Madhavan studied propagation in an LQG quantization of Smolin's weak coupling limit of Euclidean Gravity based on graphical $U(1)^3$ 'charge' network states. Building on his earlier work on anomaly free quantum constraint actions for this system, he analysed the extent to which physical states encode propagation. In particular, he showed that a slight modification of the constraint actions constructed in his previous work leads to physical states which encode robust propagation. Under appropriate conditions, this propagation merges, separates and entangles vertices of charge network states. The 'electric' diffeomorphism constraints introduced in previous work play a key role in his considerations. The main import of this work is that there are choices of quantum constraint constructions through LQG methods which are consistent with vigorous propagation thus providing a counterpoint to Smolin's early observations on the difficulties of propagation in the context of LQG type operator constructions. Whether the choices considered in this work are physically appropriate is an open question worthy of further study.
[Madhavan Varadarajan]

Causal Set Theory

A radically different, but manifestly covariant approach to quantum gravity is Causal Set Theory (CST). CST is motivated by deep theorems in Lorentzian geometry that demonstrate the primacy of the causal structure of spacetime. The causal structure of any reasonable spacetime forms what is known as a partially ordered set. Rather than quantise the geometry, in CST one quantizes this causal structure. The spacetime continuum is thus replaced by a discrete substructure, which is a locally finite partially ordered set or causal set.

The Sorkin Johnston Vacuum for De Sitter Spacetime

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 and thence particles depend 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. This has potentially very interesting phenomenological consequences, especially for the early universe. The Sorkin-Johnston (SJ) vacuum was studied for free scalar field theory in de Sitter spacetime and on causal sets that are approximated by de Sitter spacetime. In the continuum, it was shown that the SJ vacuum is not related to the O(4) Fock vacuum of Allen and Folacci nor the non-Fock de Sitter invariant vacuum of Kirsten and Garriga.

Using a causal set discretisation of a slab of 2d and 4d de Sitter spacetime, Nomaan X and Sumati Surya along with collaborator Yasaman Yazdi obtained the causal set SJ vacuum for a range of masses m0 of the free scalar field. As the volume of the slab increased, the results were seen to converge. While the 2d causal set SJ vacuum behaved as expected in the continuum, the 4d causal set SJ vacuum showed a significant departure from the continuum Motolla-Allen α-vacua. It was moreover well-defined for both the minimally coupled massless and the conformally coupled cases. This is at odds with earlier work on the continuum de Sitter SJ vacuum where it was argued that the continuum SJ vacuum is ill-defined for these masses. Their results hint at an important tension between the discrete and continuum behaviour of the SJ vacuum in de Sitter and suggests that the former cannot in general be identified with the Mottola-Allen α-vacua. This work is submitted for publication.
[Yasaman Yazdi (University of Alberta, Canada), Nomaan X and Sumati Surya]

Spatial Geometry from Causal Set Theory

The causal set approach to quantum gravity assumes a fundamental spacetime discreteness with the continuum replaced by a locally finite partially ordered set. One of the challenges in this approach is to recover the continuum spacetime geometry from order invariants. While several topological and geometric invariants are known, it has been difficult to obtain spatial information. In recent work at the Institute, Sumati Surya along with collaborators Astrid Eichhorn, Fleur Versteegen have obtained a spatial induced distance function on the analogue of a space like hypersurface using just the ambient causal relations. In the UV, this distance function overestimated the continuum distance due to discreteness effects but beyond a mesoscale, the discrete distance reproduced that in the continuum extremely well. Extensive numerical simulations were performed to demonstrate this in 2 and 3 spacetime dimensions, for spacelike hypersurfaces with and without curvature. This work is now published in Class.Quant.Grav. 36 no.10, 105005 (2019).
[Astrid Eichhorn (University of Heidelberg, Germany), Fleur Versteegen (University of Heidelberg, Germany) and Sumati Surya]

Quantum Foundations, Information and Optics

Accelerating coherent states

It is well known that a Gaussian wavepacket disperses while evolving with the free particle Schrodinger equation, and a suitable confining potential is needed for a wavepacket to propagate coherently without dispersing and distorting. Berry in 1979 discovered that there exists wavepackets, with probability distribution having an Airy function profile, which uniformly accelerate and propagate without spreading in free particle Schrodinger equation. These wavepackets have been realised in many optical experiments. While these wavepackets have been extensively studied, the origin of uniform acceleration and non-spreading was not clear. Vivek Vyas has recently shown that these peculiar properties have their origin in the fact that these wavepackets are (Perelomov) coherent states. He found that the Galilean invariance of the free particle Schrodinger equation plays a pivotal role in giving these coherent states their unique dynamical property. So far, these coherent states have been studied only in the framework of closed systems. Currently he is working towards generalising these coherent states to open quantum systems which take into account the interaction of these states with the environment. The goal is to study the robustness of these accelerating states against dissipation and forcing. He is also attempting to generalise these coherent states to higher spatial dimensions.
[Vivek M. Vyas]

Likelihood Theory in a Quantum World: tests with Quantum coins and computers

Overview:

Supurna Sinha and Joseph Samuel in collaboration with Arpita Maitra investigated the issue of quantum state determination by 'tossing' a quantum coin and found that quantum entanglement leads to an improved strategy in state determination compared to one where a string of qubits were measured individually. They demonstrated this on the simulation facility of IBM quantum computers.

Details:

By repeated trials, one can determine the fairness of a classical coin with a confidence which grows with the number of trials. A quantum coin can be in a superposition of heads and tails and its state is most generally a density matrix. Given a string of qubits representing a series of trials, one can measure them individually and determine the state with a certain confidence. During 2018-19, Supurna Sinha, Joseph Samuel and collaborator Arpita Maitra have shown that there is an improved strategy which measures the qubits after entangling them, which leads to a greater confidence. This strategy was demonstrated on the simulation facility of IBM quantum computers. This work is now available as an article titled "Likelihood Theory in a Quantum World: tests with Quantum coins and computers" in arXiv:1901.10704
[Supurna Sinha, Joseph Samuel and Arpita Maitra (CR Rao Advanced Institute of Mathematics, Statistics and Computer Science, Hyderabad)]

Nonequilibrium Quantum Dynamics

Dynamics of hybrid junctions of Majorana wires

Overview:

Dibyendu Roy and his collaborator Nilanjan Bondyopadhaya have investigated the dynamics of hybrid junctions made of topological superconductor (TS) and normal metal (N) wires. They considered an X-Y-Z configuration for the junctions where X, Y, Z = TS, N with the wires X and Z being semi-infinite and in thermal equilibrium. Upon connecting the wires X and Z through the short Y wire at some time and numerically studying the time-evolution of the full device they found a persistent, oscillating electrical current at both junctions for TS-N-TS device even in the absence of any phase or voltage or thermal bias. The amplitude and period of the oscillating current depend on the initial conditions of the middle N wire indicating the absence of thermalization. This zero-bias current vanishes at a long time for any of X and Z being an N wire or a TS wire near a topological phase transition. Using properties of different bound states within the superconducting gap, they have developed a clear understanding of the oscillating currents.

Details:

Josephson junctions are an essential building block of modern quantum electronics and precision measurements. Such junctions with exotic TS hosting Majorana quasiparticles have been predicted to be an integral component of future quantum devices, e.g., fault-tolerant quantum computers. Several experiments have recently observed significant evidence of Majorana quasiparticles in electrical transport measurements in hybrid junctions of engineered TS wires and N wires.

While there are many theoretical studies over the last two decades for steady-state transport in hybrid junctions of TS wires, a very fundamental question remains unexplored: Is there a unique nonequilibrium steady-state in such hybrid devices of TS and N wires? A negative answer to this question would pose a severe challenge to the validity of steady-state transport analysis in these systems. During the past year Dibyendu Roy and Nilanjan Bondyopadhaya have attempted a solution to the above important problem.

They considered an X-Y-Z configuration for the junctions where X, Y, Z = TS, N (see Figure 1). They assumed the wires X and Z to be semi-infinite and in thermal equilibrium. The wires X and Z were connected through the short Y wire at some time, and time-evolution of the full device was studied numerically. They were particularly interested in checking whether the properties of the full system in the long-time limit becomes independent of the initial conditions on the middle Y wire which would indicate a unique steady-state. Three different cases were investigated, namely an N-TS-N, a TS-N-TS and a TS-N-Z device with Z being an N wire or a superconducting wire which can be swept through a topological phase transition accompanied by a gap closing in its band. They found that while there is a unique nonequilibrium steady-state in an N-TS-N device, surprisingly it is absent in a TS- N-TS device which is widely studied for fractional Josephson effect. The TS-N-Z device showed a unique steady-state only when Z was an N wire or a TS wire near the topological phase transition. They especially found a persistent, oscillating electrical current at both junctions of the TS-N-TS device even when there is no thermal or voltage bias, and the TS wires are identical. They related the above findings to the presence of different bound states (states with energy within the superconducting bulk-gap) in the full system and have developed a simple yet clear understanding of the necessary conditions for a unique nonequilibrium steady-state in these hybrid devices. Their results will be of much use for direct detection of so-called fractional Josephson effect in the Josephson junctions of TS. The article has been submitted for publication and is also available on arXiv:1812.10149.

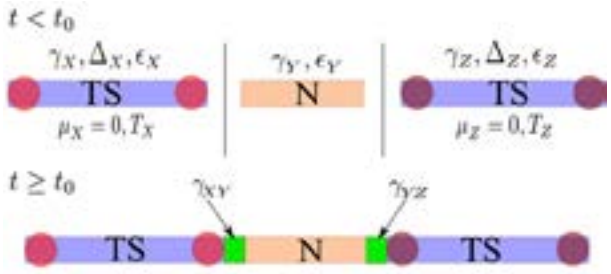


Figure 1. Schematic of a hybrid device of X-Y-Z configuration where X, Z are made of topological superconductors (TS) and Y is a normal metal (N). It shows the individual components of the device before (top) and after (bottom) their coupling via the tunneling rate γ_{XY} and γ_{YZ}. The red dots indicate Majorana bound states appearing at the edges of the TS wires.

[Dibyendu Roy and Nilanjan Bondyopadhaya (Visva-Bharati University, Santiniketan)]

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 Advances in Space Research, Astroparticle Physics, Astrophysical Bulletin, Astrophysics and Space Science, Monthly Notices of the Royal Astronomical Society, Astrophysics, Astrophysical Journal, Astrophysical Journal Letters, Astronomy and Astrophysics, Experimental Astronomy, Journal of Cosmology and Astroparticle Physics, Journal of Astrophysics and Astronomy, Journal of Plasma Physics and Science China Physics: Mechanics and Astronomy.

The Soft Condensed Matter group has its work published in ACS Applied Materials and Interfaces, Biophysical Journal, Brazilian Journal of Physics, Chemistry Select, ChemPhysChem, Dyes and Pigments, European Biophysics Journal, European Physical Journal, Journal of Chemical Physics, Journal of Physical Chemistry B, Journal of Physical Chemistry C, Journal of Analytical Chemistry, Journal of Materials Chemistry, Journal of Molecular Liquids, Journal of Molecular Structure, Liquid Crystals, Materials Chemistry Frontiers, Micromechanical Journal, Nature Communications, New Journal of Chemistry, Physical Review Letters, Soft Matter and Physical Biology.

Publications of the Light and Matter Physics group can be found in Annals of Physics, Applied Optics, Applied Physics A: Material Science and Processing, Applied Physics B: Lasers and Optics, Carbon, Journal of Physics D: Applied Physics, Journal of Optical Society of America B, New Journal of Physics, Optics Materials, Optics Express, Optics Letters, Physics of Plasma and Physical Review A.

Theoretical physicists at RRI use journals like Classical and Quantum Gravity, International Journal of Quantum Information, Journal of Statistical Mechanics: Theory and Experiment, Journal of Physics A: Mathematical and Theoretical, Physica A, Physical Review E, Results in Physics and others as a medium to share their knowledge with the national and international scientific community.

130 papers with RRI members as authors and/or co-authors were published during 2018-19. There were 10 publications in conference proceedings and 16 publications (14 in journals and 2 in conference proceedings) are in press.

Members of the Institute also regularly publish books and/or articles for popular science magazines to reach out to a wider audience beyond that of specialized technical and scientific journals. During the past year, RRI members wrote 3 book chapters. 5 popular science articles were published in Resonance, Current Science and Bengali Language literary magazine Desh and Kalpabiswa.

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 Bruno Laburthe-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 - February 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 5,95,00,000 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	Templeton grant 57758 awarded by John Templeton Foundation	Project title - Unveiling the Nature of quantum reality: a theoretical and experimental approach employing non-destructive weak measurements. Co-PI - Alexandre Matzkin(CNRS, France) Total grant amount – EUR 77, 880 Grant released – EUR 70,902. Grant period - November 2015 - July 2018.
		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 6,95,80,000 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

	Name	Extramural grant	Details
		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
5	Biman Nath	Indo-Israel grant No. 504/14	Project title: Galactic outflows and the sky's biggest shock. PI - Prateek Sharma, IISc. Total grant amount (Indian side): INR 86,00,000. Project duration: 4 years, started in 2014.
		Indo-Russian grant No P270	Project title: The 500 parsecs around the galactic center Total grant cost: INR 5,00,000 Received so far: INR 2,50,000 PI's: Biman Nath, Yuri Shchekinov, Lebedev Physical Research Institute, Moscow, Russia Project Duration: Sep 2017 – August 2019
6	Shiv Sethi	1) Indo – US Science and Technology Forum IUSSTF/JC-009/2016	Project title: "Probing Fundamental Nature of Dark Matter through upcoming 21 cm Signals from Reionization Epoch" from the Indo-U.S. Science and Technology Forum (IUSSTF) under 2016 the call of Joint R&D Networked Joint Center program. Indian PI: Shiv Sethi, CoPI: Subinoy Das, IIA US PI : Marc Kamionkowski, John Hopkins, Adrienne Erickcek, University of North Carolina Total grant money: INR 27,24,350 Received so far: INR 6,00,000 Duration: May 2017-April 2019
		2) 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	Project title: High throughput electrical detection of Malaria infection in single RBC's under low parasite density Grant Money INR 50,00,000, Received so far INR 18,00,000 Project duration: January 2018 – July 2019
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

	Name	Extramural grant	Details
			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 95,00,884 lakhs Received so far: INR 20,57,000
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 Funds yet to be released.
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 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 Date Started: 26.11.2018 Total amount: INR 18,30,000 RRI share: INR 3,35,000

	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

	Name	Fellowship	Details
3	Gautam Soni	DBT- Ramalingaswami Fellowship	Project title - Epigenetic gene sequencing by chromatin condensation using nanodevices. Fellowship started in January 2014. Total grant amount – INR 88,00,000 Received so far– INR 37,00,000 Duration: 5 years.
4	Urbasi Sinha	Homi Bhabha Fellowship	INR 25,000 per month plus contingencies for travel/ books connected with research Duration: July 2017 to July 2019.
5	Sayantan Majumdar	SERB Ramanujan Fellowship	Total research grant amount: INR 38,00,000 Duration: 5 years Received so far: INR 7,60,000
6	E Krishnakumar	Raja Ramanna Fellowship	Total Fellowship Amount: INR 40,50,000 Received so far: INR 13,50,000 Duration: 3 years
7	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

TAA excellence award for E Krishnakumar

RRI emeritus scientist E Krishnakumar (LAMP) was awarded the TAA Excellence Award 2018 by the TIFR Alumni Association (TAA). This award was in recognition of his distinguished contributions to science and to TIFR.

Recognition for Pratibha R

R Pratibha (SCM) has been invited to deliver a plenary "Sturgeon lecture" at the 2019 British Liquid Crystal Society conference in Leeds University in the UK. This is one of the highest honors the British Liquid Crystal community can bestow.

Best poster presentation award for Saikat Das

Saikat Das (AA) poster presentation at the International School on Astroparticle Physics 2019 during 1-9 March at the Pierre Auger Observatory in Argentina was selected as the best poster presentation in this School.

Recognition for Urbasi Sinha

Urbasi Sinha was recognized as one of top 100 scientists and also one of top 26 female scientists in Asia by the 2019 edition of Asian Scientists 100.

Research Facilities

Electronics Engineering Group

The Electronics Engineering Group (EEG) of the Institute has supported the engineering activities of the experimental groups of the Institute. The engineers and the technical staff of EEG have the capability to develop state-of-the-art instrumentation for carrying out scientific experiments. Over the past couple of decades, the group has built several instruments using cutting edge technology and has contributed significantly to the growth of basic science. The group keeps itself up-to-date with the latest trends in technology by using the most modern devices available in the market along with simulation tools for optimizing the performance of the electronic circuits that it builds. It is gaining expertise in specialized fields like RF over fibre, system on chip (SoC) and Graphics Processing Units (GPU).

During 2018-19 the Electronics Engineering Group was involved in several research projects including X-ray astronomy, Brain Computer Interface (BCI) and experimental cosmology. Its contribution to various projects is highlighted in the paragraphs below emphasizing more on its expertise and ability to work with challenges.

Exploration of antenna performance on water surface

Extensive simulation results and experimental measurements of ground based antenna indicated strong dependence of the radiation characteristics on the electrical properties of real earth. For real earth, which is composite and inhomogeneous in nature, use of a single dielectric constant and electrical conductivity often inaccurately models its electrical characteristics. When simulation of electromagnetic behaviour of radiating structures is carried out with this assumption, the results might differ significantly from the field measurements.
Also, real earth, because of its low permittivity and low conductivity, would result in poor radiation efficiency. To minimize the discrepancy between the simulation and the measurement results and to improve the radiation efficiency of the antenna, water was identified as a medium to replace real earth. Water, with its large dielectric constant and moderate conductivity, is expected to enhance the performance characteristics of the antenna.

Figure 1. Conical monopole antenna being characterised for its impedance and radiation characteristics on the surface of water in Agara Lake situated near Banashankari, south of Bangalore. A small raft designed in-house was used to float the antenna and measurements were carried out in-situ while communicating with equipment at the antenna via optical fiber.

Four different types of antennas designed to detect the epoch of reionization signal in the frequency range 40-200 MHz were used to understand the effect of water on the radiation characteristics of the antenna. Return loss measurements on water surface were made in Agara lake situated near Banashankari, South of Bangalore and iterations to improve antenna performance is in progress. A raft designed in-house was used to float the antenna on the water surface.

Graphics Processing unit based correlation spectrometer

Electronics Engineering Group is embarking on a new capacity building: that of using a Graphics Processing Unit (GPU) for building correlation spectrometers in a hybrid configuration along with Field Programmable Gate Array (FPGA) devices. GPU, being a highly parallel structure, is designed for processing massive data in parallel. It is already being used extensively across the globe for processing digital data. The inaccuracy generally seen in the data processed by a typical FPGA because of finite word length in its data representation is overcome significantly in a GPU. Due to its efficient image processing capability, it is finding several applications in the field of radio astronomy.

Figure 2 Hardware setup used for characterizing the FPGA-GPU based hybrid correlation spectrometer

In the Raman Research Institute, a hybrid correlation FX spectrometer is being developed using both FPGA and GeForce GTX 1050 GPU, for a science project of detecting distortions in the spectrum of the cosmic microwave background radiation in the frequency range of 2-4 GHz. C programs are being developed in Compute Unified Device Architecture (CUDA) - a parallel computing platform for processing the data.

Big Data processing for SKA pulsar search

One of the staff of Electronics Engineering Group (EEG) participated in the development of Field Programmable Gate Array (FPGA) based high-performance power-efficient processing for the Square Kilometre Array (SKA) pulsar search programme. Square Kilometre Array is an international facility being built to address several fundamental questions about the origin and evolution of the Universe. The design methodology adopted in building the FPGA system has been approved by SKA pulsar search engine review and is moving ahead for its implementation.

Brain Computer Interface system for subjects suffering from motor disabilities

Electronics Engineering group has been working towards developing systems which operate by sensing signals generated in the brain, for a dedicated action intended by the subject. To get the sensing signals from the brain, Motor Imagery is being used. It is a mental process in which the subject simulates a given action. Mu waves generated as a consequence of electrical activity are sensed by the electrodes placed on the scalp. They are amplified by a bio-amplifier and analysed with the help of an in-house developed user interface. The entire instrumentation required for this process involving from sensing to analysis has been developed by the technical staff of the Electronics engineering group.

Figure 3. Brain computer interface experimental setup based on Motor Imagery

The electronics engineering group is also engaged in developing a Brain Computer Interface speller which helps patients having restrictions on their capacity to communicate. Patients can be made to write text on the computer screen with the help of a speller, which spells out words based on EEG signals of the subject. In this methodology, patient is asked to concentrate continuously on a selected letter being flashed at a selected frequency. By monitoring the Steady State Visually Evoked Potentials (SSVEP) developed, the intended letter could be determined and used for forming the words.

Figure 4. Typical experiment set-up for the Speller

Development of a scientific instrument for detecting X-Ray polarization in space

The X-ray polarimeter (POLIX) is a scientific instrument (payload) being built at the Raman Research Institute for detecting the polarization of celestial sources. It will be launched into space with the help of a dedicated satellite mission of ISRO namely X-ray Polarimeter Satellite (XPoSat). After successfully crossing the milestone of the preliminary design review (PDR), efforts are towards converting the laboratory model of subsystems of the instrument to Qualification and Flight Models.

In the process of conversion, the instrument built was also made compatible with the space standard by incorporating different standards as recommended for the space mission. The receiver system was made Cold sparing compatible for protecting its subsystems when not powered ON. Electronics Engineering Group has been continuously gaining experience in the payload design and its validation through vibration and thermal tests.

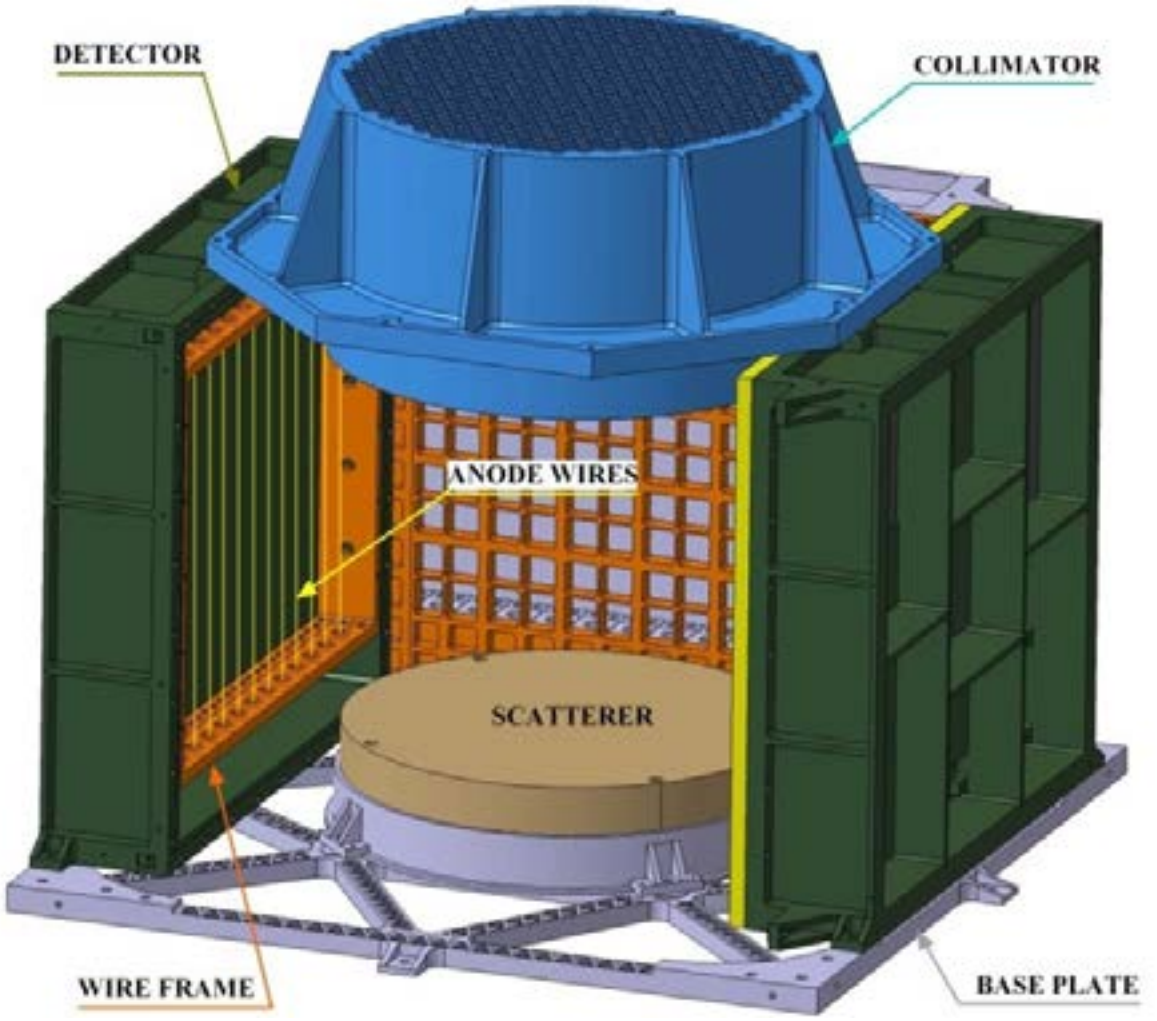


Figure 5. POLIX payload integrated view with one detector removed

Electronics Engineering Group's contribution to Outreach programmes of the Institute

EEG has always been at the forefront when it comes to involving students in the on-going engineering developmental activities of the Institute. It is doing so by educating them, imparting them relevant technical knowledge and encouraging them to get hands-on experience in designing and building RF and digital receiver systems.

EEG's public outreach is through four different ways:
i) by working with students coming through the Institute's Visiting Students Programme ii) by interacting with public during open day celebrations iii) by taking part in the CHERA summer school programme organized by RRI and iv) training students of various academic institutes in building radio telescopes and observing the sky.

Visiting students programme (VSP) is a programme introduced by the Institute with the primary intention of providing opportunities to the students to work with both scientific and engineering staff of the Institute and

take part in its various research activities. Students are being trained every year in both experimental work and theoretical studies. Under the guidance of EEG staff, VSP students built in the recent past i) a simple radio receiver for detecting bursts from Jupiter and ii) a 21 cm receiver based on software-defined radio (SDR) module for observing 21cm line from the sky. These receivers were built entirely by the students by using the locally available components and modules.

Figure 6. Staff of EEG having discussion with the participating students during the Open day celebration

During the open day celebration conducted by the Institute on February 28th 2019, members of EEG conducted several simple experiments to demonstrate the fundamental concepts involved in various activities of the laboratory. Toy models were also made for some of the scientific experiments for easy understanding. Figure 6 shows staff of EEG involved in conversation with the participating school children.

CHERA is a summer school programme organized by the Raman Research Institute and Indian Institute Astrophysics every year. In this programme, participating students will be trained and given exposure to various research activities. They will also be encouraged to get hands-on-experience in building simple receiver systems for radio astronomical applications.

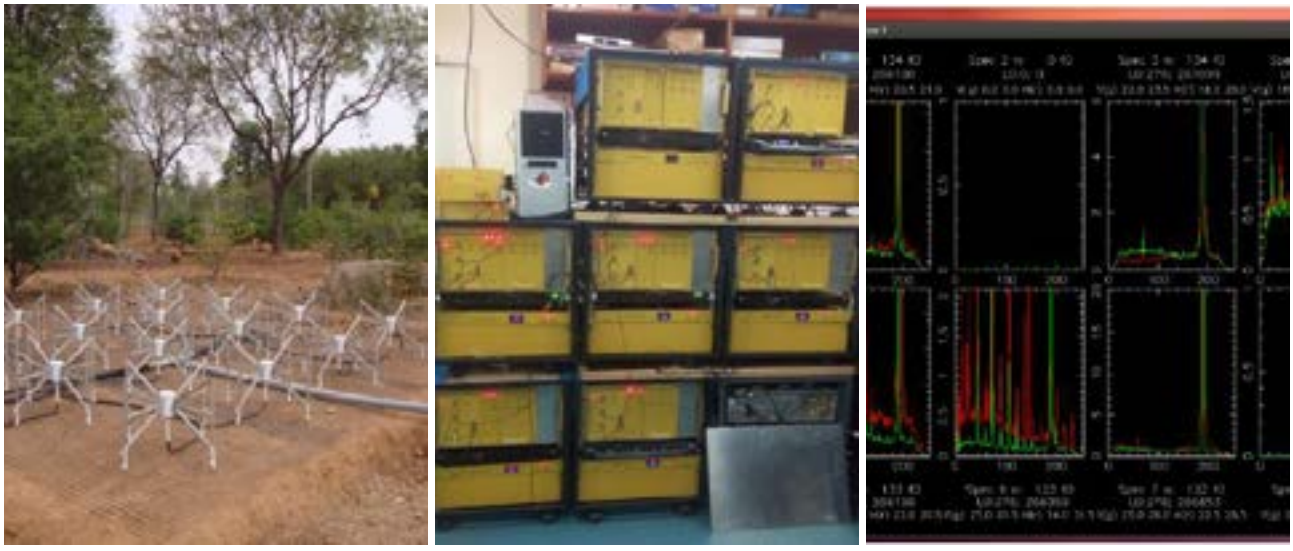


Figure 7. (Left) 4x4 bow-tie antennas forming one tile (Middle) Receiver systems kept ready after validation to shift to different academic institutions. (Right) Output spectra of different tiles at 140 MHz over a bandwidth of 14 MHz. Observe the presence of radio frequency interference

The Indian Sky Watch Array Network (SWAN) is another initiative from the Raman Research Institute. It is aimed at nurturing future generations of talented radio astronomers in India. Students also get hands-on experience by directly participating in various design stages of the array network. The array network is capable of operating over a decade bandwidth spanning from 50 MHz to 500 MHz. However, at present the operating bandwidth is restricted to 14 MHz around 140 MHz in Gauribidanur field station due to the presence of unmanageable radio frequency interference. The backend receiver is able to operate in two discrete modes: i) raw voltage acquisition mode and ii) stokes computed acquisition mode. Six complete receiver systems validated completely for their functionality are kept ready for sending them to different institutions. Each academic institution will be given one antenna tile along with the front end and backend receiver systems. They will be trained to use the radio telescope and conduct sky observation.

Mechanical Engineering Services

The Mechanical Engineering Services (MES) provides for 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 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 2018-19.

For the Nanoscale Physics of Soft and Living Matter laboratory a rigid microscopic stage using brass for the base and aluminum for side support was fabricated using the CNC router machine. The brass plate was provided with multiple holes that allows freedom in the (x,y) positioning of optical components. For the same lab the CNC router was also used in the fabrication of a copper Faraday cage, a device for electromagnetic shielding.

MES is also equipped to perform precision engineering. Using the CNC precision machine, they fabricated 25mm posts and clamps for mounting components on to an optical table using stainless steel 316. These components are in use in the Quantum Mixtures laboratory. A requirement for movable mirrors on the optical table of the Ultrafast and Nonlinear Optics laboratory was achieved by coupling motors with mirror mounts.

For the Quantum Mixtures lab, the MES designed and fabricated an experimental setup that could measure the magnetic field of a coil at various positions. The setup consists of a linear rail and sliding block with provisions for holding a measurement probe. The sliding block has scale gradations for accurate linear positioning.

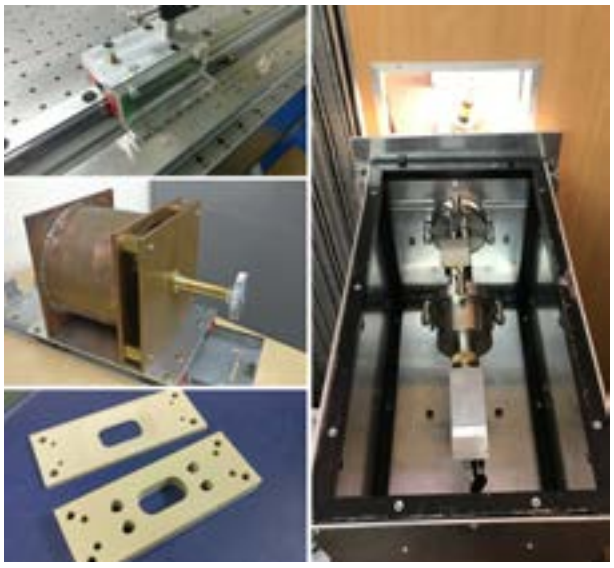
Designed and fabricated a "peek oven" for LAMP group. The setup consists of brass crystal holders, a heater as well as provisions for a temperature sensor.

Designed and fabricated a high voltage vibration jig for sine vibration testing of the high voltage module that will be used in each of the detectors of POLIX. Their design also accommodated the holes necessary for it to be mounted on the vibration shaker of the Earthquake engineering and vibration research center of Central Power Research Institute.

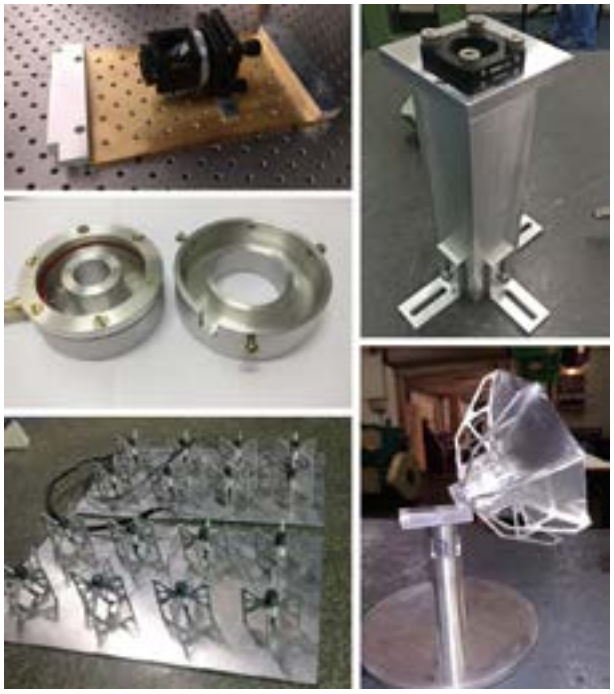
The X-ray shield structure for the 12m X-ray beamline was designed and fabricated for the purpose of shielding people from high energy X-ray emissions from the X-ray generator. Utmost care was taken while designing in order to prevent X-rays escaping the barrier. The design was primarily for protection against back emissions since most of the forward emission is concentrated through a very narrow slit along the length of the beamline. The shield structure is primarily made up of four-mm thick lead as the basic shield material, sandwiched between two aluminum sheets for rigid support as well to mount it to the mild steel frame. The design also incorporates easily removable faces for easy access to instruments.

Designed and fabricated a variable volume microwave cavity for the Laser cooling and quantum optics laboratory. Flat plates of copper were machined in the CNC router and the cylinder was turned to the required dimension using conventional lathe. A fine thread brass screw rod was machined for precise movement of inner copper plate. A hole was drilled through the cavity for passing laser through it. The microwave cavity was mounted on a linear motion block that slides onto linear mounted rails mounted on an aluminum base plate.

Designed and fabricated a three-piece vacuum chamber for the Biophysics group that will act as a PDMS cell stretcher. The chamber was fabricated using aluminum and was provided with a rubber gasket that serves the dual purpose of protecting the PDMS from the comparatively sharp edges of the aluminum components as well as providing a vacuum seal. These components were fabricated using the lathe.



Left (Top to bottom): A linear rail and sliding block with scale graduations for precise linear positioning; microwave cavity with provisions for precise positioning; customized holder for microscopy. Right: Shield for protection against X-rays.



(Left panel, from top) A rigid microscopic stage for mounting optical components; PDMS Cell stretcher; miniature model of bow-tie shaped antennas that the Institute uses for radio astronomy research. (Right panel, from top) An aluminum camera mount for the 'alcohol-sensing in blood diagnostics' demonstration; a miniature model of a dish antenna.

Library

Library Collection:

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 70528 comprising of books and bound volumes of journals. Out of this, 29034 are books and 41494 are bound volumes of journals. Library subscribed to 25 e-journals and 55 print journals during this year. Library has a total of 670 non-book materials. During the past year the Library acquired 22 e-books and 'Grammarly' a software that aids writing skills. RRI Library has also taken membership of arXiv.

Library activities:

Renewed partnership of RRI Library with National Knowledge Resource Consortium for next three years has brought in online access to 4600 journals published by 15 publishers up to 2019. RRI library is a content partner to the National Digital Library of India project of IIT Kharagpur. Research output of the Institute 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 five theses submitted for the award of the doctorate was done at the library. ResearcherID of the entire faculty is regularly updated. Article processing charges of 13 papers were handled by RRI library. Partnering with Gubbi Labs, a social media centre, three research results of RRI appeared as news items in popular dailies during 2018-19. RRI library plays a major role in outreach activity by donating Hindi books to needy school libraries.

Library Automation and Digital Library:

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

The Raman Research Institute Digital Repository (RRIDR), 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. Thesis submitted to RRI is also uploaded to the repository. During the past year, continued efforts were towards digitization and upload of archival materials, photographs, and audio/video. Number of uploads during this year are 750 and the total records on RRIDR are 10230. "Imprints-collection", an offshoot of RRIDR continues to thrive with regular updated information. This bio-bibliographic database currently has 29 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.

Another major project taken up during this period was to design and build a digital bio-bibliographic database of Sir C V Raman's research students at RRI during 1948-1970. Raman had 7 students. This database, built by the library has profile pages of each of his students with further links to their publications, photographs and any other relevant information. This was made available for public viewing on National Science Day.

Training activity:

RRI library has kept up the tradition of supporting manpower development programs by giving internship training to students from Bangalore University, Bengaluru; Kuvempu University, Shimoga; Shri Jayachamarajendra Government Polytechnic for Women, Bengaluru. During 2018-19, ten students from these library schools were trained.

Other Events:

1. Many events like author workshop, training programs to use the information products were conducted. A public lecture to celebrate the National Library week was organized. Mr. Suresh Heblikar, a well-known environmentalist and Kannada filmmaker addressed the gathering.
2. Library had theme display of books on the occasion of Republic day of India. Book exhibition was also organized during this year.

Computer Group

The Computer group manages and maintains the IT infrastructure and handles various computing needs of the Institute and provides support for the computing facilities. During 2018-19, apart from routine work the computer group undertook the following activities:

- The Digital Repository of the SWAN project was migrated from a physical server to a virtual server.
- Renewal and updating of end-point Anti-virus licenses for computers and laptops in the Institute was carried out. Ten additional Matlab network licenses and few additional existing and new Matlab Toolboxes were procured and installed.
- Provided support in adding new features, managing and maintaining the KOHA Library Management System.
- A 150KVA Modular UPS was procured for the Data Center to power the servers.
- Set up a video conference room in the Library Map room. A 65" LED Full HD TV, computer and HD webcam with integrated speaker and microphone was identified and procured. These were fixed and tested in the Map room in the Library.
- The NKN internet links of the Indian Academy of Sciences (IAS) and our Institute were interconnected to provide a failover link on failure of the primary link due to fiber cuts. This has now enabled uninterrupted internet service. A fiber cable was laid between the service room in IAS and the cottage in RRI and connected to a spare fiber pair, which extends up to the server room.
- Online examination was conducted for the 42 shortlisted students for the Professor Harry Messel International Science School 2019. An Open Source examination software, TCExam, was used for the examination. The students appeared for the examination from their homes and were monitored using Cisco Webex which enabled connecting to their webcam and microphone. A mock test was conducted a week before for the candidates to familiarize them with the online examination portal and the monitoring procedure. The final selection, from the 16 shortlisted students, was done based on the interview conducted remotely using Cisco Webex.
- Set up two DNS servers for 'rri.res.in' domain for greater and easier control and maintenance. The DNS entries were earlier maintained by the NKN DNS servers. Changes were made in the domain registry to point to the new DNS servers.

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 2018-19, 103 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 8 PhD theses were completed and submitted for review:

S.N	Name	Thesis Title
1	Nafisa Aftab	Orbital Temporal and Spectral Properties of X-ray Binaries
2	Jagadeesh R V	Electrochemical studies on Functionalized Indium Tin Oxide (ITO) and Graphite oxide (GO)surfaces
3	Anirudh Reddy	Quantum Measurement and Cloning of States
4	Kumar Shivam	Geometry and Physics of Entanglement
5	Deb Sankar Banerjee	Active Hydrodynamics of Actomyosin Elastomer with Turnover during Tissue Remodeling
6	Deepak Gupta	Fluctuations and large deviations in non-equilibrium systems
7	Aswathanarayana Gowda	Synthesis and Characterisation of Some Novel Banana and Discotic Liquid Crystals
8	Karamveer Kaur	Dynamics and Statistical Mechanics of Keplerian Stellar Systems

Six PhD theses were awarded:

S.N	Name	Thesis Title
1	Karthik H S	Quantum information theoretic approach to explore non-classical correlations and uncertainty
2	Lijo Thomas George	A study of radio relic and radio halo emission in galaxy clusters
3	Saurabh Singh (JAP)	Observational Constraints on Global 21-cm Signal from the Epoch of Reionization
4	Priyanka Singh	A Study of Multiple Probes of the Circumgalactic Medicum
5	Rahul Sawant Vaijanath	Interactions between ultra cold dilute gas of atoms, ions and cavity
6	Gayathri Raman	Multi-wavelength study of X-ray reprocessing in Low Mass X-ray Binaries

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 2018-19 there were 18 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, 32 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 2018-19, 94 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, Argentina, USA, Germany, France, Israel, Canada, Sweden, Italy, Spain, China, Japan, Bangladesh and UK

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 122 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 2018-2019, 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

Public Outreach

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 and workshops. 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. All of these continued in 2018-19 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.

Student visitors to RRI campus

3rd May 2018

Seven meritorious high-school students along with their teachers from 'Aryabhat' (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 2017-18. Following a welcome speech by Dwarakanath K S (AA) the students were taken on a tour of the CMB Distortions laboratory and the X-ray laboratory. In the CMB Distortions lab Saurabh Singh (AA) explained the science aspects of the ongoing experiment while the technical aspects were explained by EEG group members Raghunathan A, Girish B S and Srivani K S. In the X-ray Astronomy lab Gopalakrishna (EEG) and Rishin P V (EEG) explained the ongoing research at the lab towards building POLIX, an X-ray polarimeter.

11th May 2018

Twenty-five students and one staff from Radboud University, Netherlands visited RRI. Sandeep Kumar (SCM) delivered a talk and interacted with the visitors. Subsequent to the talk the students were given a tour of his lab.

19th September 2018

Sixty students and faculty members from Lady Doak College, Madurai visited RRI. Dwarakanath K S (AA) interacted with the students. This was followed by visits to the Ultrafast nonlinear optics lab and Radio astronomy labs. RRI PhD students as well as engineers who are building antennas and receivers for various experiments interacted with the visitors.

7th November 2018

Fifty students and three teachers from MES – B R Subba Rao PU College, Vidyaranyapura, Bangalore visited RRI as part of their science activities and to commemorate the birth anniversary of the Institute's founder Sir C V Raman. Udayashankar (AA) interacted with the students, which was followed by a visit to the Electronics and Engineering Group (EEG). The visit concluded with a guided tour to the Raman Museum.

30th November 2018

Sixty-five students of tenth grade and four teachers from Jnanakshi Vidyaniketan, Bangalore visited the Institute. K S Dwarakanath (AA) interacted with the students followed by visits to the EEG and Chemistry laboratories. The visit concluded with Sasikumar giving a guided tour of the Raman museum.

1st February 2019

Five tenth standard students from Army Public School, New Delhi visited RRI. This visit was arranged while the students were in Bangalore to participate in Indian RoboCupJunior Nationals 2018-19. A Raghunathan (EEG) interacted with the students and gave a tour of EEG laboratories.

17th January 2019

Ten students and one faculty from CMS College, Kottayam, Kerala visited the Institute. Reji Philip (LAMP) interacted with the students followed by a visit to the Ultrafast nonlinear optics lab. The event concluded with a guided tour of the Raman museum.

25th February 2019

Sixty-five students from Breakthrough Science Society visited the Raman Museum.

28th February 2019

Forty students from Periyar Maniammai Institute of Science and Technology Tamilnadu, thirty students from Parikrma Foundation, Bangalore and ten students from Wise Gurukula, Bangalore along with general public visited

RRI and participated in the Institute's National Science Day celebrations. For a description of the day's activities the reader is requested to visit the Events section of this report.

27th March 2019

Forty-two MSc Chemistry students and two faculty from Indian Academy Degree College, Bangalore visited RRI. The visit started with an interaction with Yuvaraj A R (SCM) and Ashwathnarayana Gowda (SCM) in the RRI main auditorium. The topic of discussion was 'Introduction to and synthetic designing of liquid crystals'. This was followed by visits to the chemistry lab and Raman museum. On the same day thirty MSc Physics students and three faculty from Bangalore North University Kolar and ten MSc Physics students from Providence Women's College, Calicut visited RRI. Joseph Samuel (TP) interacted with the students. This was followed by visits to the Ultrafast nonlinear optics lab and Raman museum.

(Left & Center) LAMP group members interacting with student visitors from Lady Doak College, Madurai (Right) Meritorious high-school students from Aryabhat Foundation, Gwalior.

Student workshops and visits to Gauribidanur field station

Despite several student internship programs offered by various Indian research institutes that provide useful research experience to typically a few hundred students each year, an overwhelming majority of bright and motivated students still remain unexposed to the exciting developments and research opportunities in radio astronomy. Due to the lack of exposure at an early stage, much of the talent remains untapped. Initiatives such as the "Radio astronomy winter school for college students" (RAWSC, since 2008) and the "Pulsar observing for students" (POS, since 2012) aim to bridge this gap. These programs have provided such opportunity to more than 200 students so far. New programs, particularly aimed at mentoring radio measurement techniques and instrumentation skills, would complement and enhance capacity for future development in these areas.

This decade has seen an unprecedented increase in radio astronomy initiatives and related developmental activities, as well as research in general with existing and new facilities, across the world. India has a long history in radio astronomy, including instrumentation development. RRI ensures the continuity of this tradition, by training the next generation of radio astronomers and instrumentation developers in hands-on camps conducted at the Gauribidanur field station (since 2017 jointly with IIA) and at RAC, Ooty (in 2015 and 2016 jointly with NCRA). The focus in these camps is on hands-on experience with instrumentation, observation, measurement and analysis, thus distinct from the other initiatives that are already in place. In addition to the hands-on component, the two plus weeks' camp aims to introduce undergraduate and master's students to radio astronomy - basic concepts and advanced topics and techniques.

In the Gauribidanur field station students also get to know the Indian SWAN (sky watch array network) phase-0 (8-station) system closely, work with it in an uninhibited manner and conduct tests/observations in single station and interferometer modes. With such exposure, hands-on experience and involvement, the students are encouraged to follow-up their participation in the development and use of SWAN through remote access, as well as locally and at a later time when their institutes host one of the SWAN stations. It is encouraging to see the students come forward on their own to participate in the SWAN programs. At present, teleconferences with a dozen students across India happen every evening (of course, except during their exams!) in order to help them pursue their interest in SWAN and carry out real data analysis leading to imaging. To know more about the SWAN program, visit http://www.rri.res.in/SWAN/SWANRRI.html

During the past year, three such camps were conducted at the Gauribidanur field station:

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

The 2018 edition of the camp for hands-on experience in radio astronomy was organized jointly by RRI and Indian Institute of Astrophysics between 22nd June to 7th July. Ten students from IISER Pune, IIST Thiruvananthapuram, IISER Mohali, Azim Premji University Bangalore, IIT Chennai, IIT BHU Varanasi, MGM Udupi, Shivaji College University of Delhi, St. Joseph's College Bangalore and MGU Kerala attended the camp at the Gauribidanur field station.

Indian sky watch array network hands-on workshop

The Indian sky watch array network hands-on summer camp was held between May - July 2018. Twenty-three students from IISER Thiruvananthapuram, IISER Pune, IIST Thiruvananthapuram, IIT Indore, Azim Premji University Bangalore, IIT BHU Varanasi, St Stephens college Delhi, IIT Kharagpur, BITS Pilani, IIT Madras, MIT Pune and Dayanandasagar College of Engineering Bangalore attended the camp at the Gauribidanur field station.

Between 1st December 2018 and 7th January 2019 about twenty-five students from various institutions made week-long visits in batches to the station and learnt about the array (using it on site and remotely) as well as related radio astronomy aspects.

Other visits

On 15th February 2019, five students from the Joint Astronomy Program visited the field station for a day. They interacted with the students and the staff at the facility and learnt about the various radio astronomy activities going on at the field station. In addition, many students worked on developing and testing an HI (21cm) receiver setup and observing the Galactic neutral hydrogen line with it at Gauribidanur.

CHERA 2018 participants along with Avinash Deshpande (AA), Ramesh Balasubramanyam (AA) and T Prabhu (EEG) at the Gauribidanur field station

RRI at India International Science Festival, 2018

As part of its commitment to engage with the society, the Institute participates in the annual India International Science Festival (IISF) jointly organized by Ministry of Science and Technology, Ministry of Earth Sciences and VIBHA. The 2018 edition of IISF was held in Lucknow, Uttar Pradesh from 5th to 8th October, 2018. IISF is a platform for scientific institutions across the country to showcase their current research and achievements apart from dissemination of scientific knowledge.

RRI set up a pavilion at the Mega Science, Technology & Industrial Expo organized as part of IISF 2018. The pavilion was modelled as a 'science express'- a train on tracks with an engine and four compartments representing the four research groups at the Institute. The main aim of the design was to create a visually impactful pavilion while also symbolically conveying that RRI research highlights had been brought to Lucknow to share with the students there and that they are welcome to jump on board if interested! RRI PhD students Pradosh Kumar Nayak (LAMP), Rajkumar Biswas (SCM) and Saurabh Kaushik (SCM) represented RRI at the Expo and interacted with the visitors.

The pavilion displayed fourteen posters of which three were about the Institute and its doctoral, postdoctoral and visiting student programs while the rest highlighted the current research activities at the Institute. The posters on science portrayed recent results on theoretical astrophysics, cosmology and observational radio and X-ray astronomy; experimental astronomy – RRI's efforts towards design, construction and operation of telescopes for specific purposes; recent work on optical tweezers and yield stress

materials; efforts towards designing microwave cavities to induce magnetic dipole transitions; efforts towards time resolved imaging of plasmas generated by irradiating samples with lasers; efforts towards secure communications using quantum key distribution; two theoretical approaches towards unifying gravity with the other forces – Causal set theory and loop quantum gravity – along with recent results; statistical mechanics and Brownian particle diffusion; recent theoretical results in nonlinear quantum optics; efforts towards measuring the binding strength of molecules and force measurements of axons; a novel method using spin noise spectroscopy for non-destructive detection of the intrinsic atomic and chemical properties of a system; experimental studies on the interaction between mononucleotides and lipid bilayers; electro-optic properties of bent core liquid crystals as well as a novel form of liquid crystal – a gel hybrid system.

Along with the posters, the pavilion showcased miniature models of radio telescopes from the Gauribidanur field station and elsewhere as well as a model optical table with components that enable light-matter interaction studies. The pavilion also showcased a live demonstration of diagnostics for effect of alcohol on blood cells.

The RRI pavilion was visited by at least six thousand people from all walks of life and it witnessed wide and deep interactions with RRI representatives about the scientific activity at the Institute. Overall it was a satisfying and fruitful exercise that led to meaningful interactions between the Institute and the wider society.

Clockwise from top left: RRI pavilion at the India International Science Festival, 2018; Saurabh Kaushik (SCM) performing a live demonstration of diagnostics for effect of alcohol on blood cells. Rajkumar Biswas (SCM) and Pradosh Kumar Nayak (LAMP) interacting with student visitors

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 blog-posts. During 2018-19, RRI continued its commitment to research communication through regular posts on the above mentioned social media platforms. It is worth noting that many of our posts and tweets are regularly shared and re-tweeted by DST. The official RRI YouTube channel that was launched in March 2017 has during the past year grown to include playlists containing videos of lectures, talks, workshops, symposiums, videos of students and postdocs discussing their research, and archival videos. Along with adding new playlists, existing playlists were periodically updated with new videos.

The biannual RRI Newsletter is another such endeavour 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 to promoting the use and implementation of Hindi in the Institute's day-to-day official work. The main responsibility of the department is to create awareness of the OL Act and help the Institute to achieve 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.
- Letters received in Hindi were replied to in Hindi.
- The website of the Institute has both English and Hindi versions.
- The Quarterly Progress Reports regarding progressive use of Hindi are being sent to the Department of Science & Technology, Regional Implementation Office and the Town Official Implementation Committee.
- The Annual Report has been published bilingually with separate English and Hindi versions.
- Hindi fortnight was observed at the Institute from 24 – 28 September 2018 and various competitions in Hindi were organized during the celebration viz. Poem recitation, Dictation, Story writing, Newspaper reading etc.
- Hindi Divas was celebrated with great enthusiasm and festivity on 28.09.2018. The Chief Guest, Prof. L. Amjad Ali Khan, Director (Training and Development), National Institute of HRD & Advancement, New Delhi delivered a talk on "Why is Hindi the Official Language?".
- Hindi workshops were conducted on 12.06.2018, 14.09.2018, 18.12.2018 and 06.03.2019 and officials trained in the workshops were encouraged to work in Hindi.
- Meetings of the Official Language Implementation Committee were conducted on 22.06.2018, 13.09.2018, 10.12.2018 and 15.03.2019 with Specific Agendas and Action taken on the decisions taken in the Meeting was ensured.
- Active participation 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 is displayed on a daily basis on notice boards across the Institute.
- Ten phrases in English with its Hindi equivalents are displayed on the Main Bulletin boards every month for use by officials.

Others

During 2018-19, 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

Quantum frontiers and fundamentals, 2018

The realm of the very small inhabited by atoms, molecules, subatomic particles like protons, neutrons and electrons, ruled by the laws of Quantum Mechanics, is bizarre, utterly captivating, counterintuitive and hence has intrigued some of the best minds of science since its advent in the early part of the twentieth century. Since then, empirical testing of the fundamental notions of quantum mechanics aided by spectacular technological progress has enabled a comprehensive and deeper theoretical understanding of a wide range of fundamental issues. More recently, the considerable progress made in this area coupled with the applications in technologies in the microscopic domain has renewed interest in revisiting the interpretational aspects of quantum mechanics for newer insights into foundational issues and using such insights gained towards more precision technologies.

For critically deliberating upon the state of play and prospects in this research area a conference titled "Quantum frontiers and fundamentals, 2018" (QFF, 2018) was organized at RRI. The major source of funding for the conference came through a grant from the John Templeton Foundation, USA that Urbasi Sinha (LAMP group) received in 2015 towards investigating fundamental aspects of quantum measurements. RRI provided the perfect venue and attendant resources. The unique mandate of the conference was to blend appropriately quantum fundamental aspects with information theoretic applications with equal emphasis on both theoretical research and experimental quantum technologies.

The conference began on the morning of the 30th April 2018 and was inaugurated by N Mukunda. He recollected the history of this field in India and how emphasis and focus have changed with time to the present date. The conference had around 100 registered participants, many of whom were students, post-doctoral fellows and young faculty. This exemplifies the high level of interest that this field now enjoys in our country. There were around 40 invited talks, 20 contributory talks and 31 posters presented at the conference.

Experimental topics included discussions of research in quantum optics including single photon sources, cold atoms, space based quantum technologies, prospects of the quantum internet as well as other systems like nuclear magnetic resonance, graphene based systems, investigation of macro-realism in nano-mechanical oscillators to name a few. Some of the theoretical aspects discussed included studies of various aspects of quantum correlations, quantum non-locality, quantum coherence, uncertainty relations, macro-realism as well as continuous variable quantum information.

An important highlight of the conference was the panel discussion titled 'Reflections on the Indian research scenario: quantum fundamentals and quantum information' held on 2 May 2018 in the evening. Speakers comprised both senior and mid-career researchers who shared their views on the way Indian research activities in this area have been evolving. They also discussed their thoughts about future directions and about further fostering this research enterprise in India. While the overall view was very upbeat about the way the Indian research activities in this area have been growing, the panel recommended (i) forming a society for quantum information scientists in the country that will facilitate better exchange of ideas and collaboration (ii) providing more thrust to experimental research in the area and enable fruitful collaborations between theorists and experimentalists and (iii) organizing more schools on specific topics in the field to increase awareness and knowledge in the student body and thus increase the pool of researchers in the area.

On behalf of RRI, Urbasi Sinha (LAMP) delivered a special talk that highlighted the different types of research, which have been and are being undertaken in the broad area of quantum information science at RRI. This includes theoretical research as well as experimental work, especially at their dedicated Quantum Information and Computing (QuIC) lab.

Other than the rigorous and intense sessions with talks by invited and contributory participants as well as the poster session, the conference also provided plenty of opportunities for discussions among the participants not only during the meal times (all organized at the venue) but also during social events organized including visits to the Raman museum at RRI as well as an excursion to Nandi Hills and its surrounding areas.

The conference ended on 4th May 2018. During the valedictory session, R Rajaraman, member of the RRI Governing Council, appreciated the importance of the subject area and noted with satisfaction that RRI has been the host institute for such a conference. Usha Devi from Bangalore University briefly summarized the salient features of the conference. As with the inauguration, N Mukunda also formally brought the conference to a close with the declaration that RRI will host the next QFF conference in 2020.

We look forward to making "Quantum frontiers and fundamentals" a recurring conference series to serve as a platform which will bring in more technological elements for discussion in the coming years while retaining the unique flavour of merging ideas in quantum fundamentals with quantum frontiers, along with fostering the link between theoretical and experimental studies.

Group picture time for the conference participants at the iconic RRI lawn

During the panel discussion

RRI special lectures

There is a growing appreciation of the critical role that scientists play in defining the world we live in. The scientific inventiveness and creativity influence almost every facet of our living. Even the ideas of what is good for everyone are substantially influenced by support and sanction from scientists and the scientific establishments.

The numbers of PhD, post-graduate and undergraduate students at RRI has risen significantly in recent years and hence there is a need for the Institute to go beyond technical education and take a greater role in the higher learning of the students. In this context it was felt that it is time that we introduce opportunities within the Institute for dialogues that engender a greater appreciation of the role of scientists in society. Hopefully this will help the younger generation that we send out become more responsible citizens of the world, embracing the responsibility that comes with education in the widest sense.

A few members of the Institute – Lakshmi Saripalli, Udaya Shankar, V S Naresh, Irla Siva Kumar and Aditi Vijayan - have created a Special Lectures forum where people who have put in considerable thought into the science-society landscape are invited. The intention is to enable dialogues to happen in an informal setting that allows a learning together of the complexity of the relationships and an exploration of the immensity of our potential impact on society.

During the past year, there were three special lectures on diverse topics.

Lecture 1: Excavating our origins: perspectives on prehistory in India

Sometimes, in order to look forward in time, to truly understand who we are, we have to turn back and appreciate things already past, acknowledge our history. It was in this spirit that the special lecture titled 'Excavating our origins: perspectives on prehistory in India' was organized at RRI Auditorium on 21st December 2018. The popular narrative on human origins is that we originated and migrated "Out of Africa" and populated the world. In academia, the migratory details of prehistoric humans are far from settled. Human origin is a constantly evolving narrative. What is the prehistoric record of human origins in India? Why did recent excavations at Attirampakkam, a village in Tamilnadu and other sites along the southeast coast of India lead to a paradigm shift and intense global debates on the timing and patterns of human migrations out of Africa and across Asia? These were some of the questions that were raised and answered by the speaker Professor Shanti Pappu, a renowned archaeologist at the Sharma Centre for Heritage Education in Chennai, who has done pioneering research in South Asian prehistory.

The talk focused on her recent excavations at Attirampakkam that led to paradigm shifts in our understanding of the prehistoric record of India and questioned timing and nature of human migrations out of Africa and into Asia. Shanti Pappu gave us a taste of how archeological excavations take place and the tools that are used in modern day archaeology. She further discussed the evolution of tools used by prehistoric humans through different ages pointing out that the complexity of a tool depends on its utility and intellect of its maker; seems like our ancestors were very artistic too as evidenced by embellishments on tools which have only aesthetic value! She explained to us the challenges faced by Indian archeologists, including destruction of excavation sites as a result of rampant urbanization and her teams' commitment towards building community resources by regularly enlisting the help of local populace for conservation. The talk was followed by an informal discussion session at the library block terrace where these topics were discussed further over tea and snacks.

Through her intriguing talk and the subsequent discussion session Shanti Pappu was able to ignite curiosity and wonder in the minds of many in the audience about the secrets held just below the surface of the Earth!

Lecture 2: Fraternity: The Missing Link in India's Democracy

Dr. Harsh Mander a well-known social activist, human rights and peace worker, writer, columnist, researcher and teacher who works with survivors of mass violence, hunger, homeless people and street children delivered the second lecture titled 'Fraternity: The Missing Link in India's Democracy' on 11th January 2018.

Dr. Mander began his talk with a commentary on the current social situation. In the past few years, mob lynchings have become a common occurrence. Such lynchings have exposed a high degree of apathy towards victims and their families from the community at large. Despite being cruel and completely devoid of humanity, the public outrage at these acts is minimal. Through this talk he wished to make us aware of this apathy. Towards the end of his talk he shared clips from a documentary made as a part of his initiative called "Karwan-e-Mohabbat" (Caravan of Love), a crowd-funded effort to meet with the families of the victims of mob lynchings. The ten-minute documentary unraveled a story of pain, sense of loss and helplessness. The sheer volume of human tragedy moved many in the audience

The discussion meeting that took place after the talk followed the same theme. Harsh Mander dwelled on the role of economics in exacerbating social injustice. He also spoke about how transforming the education system of our nation can turn children into empathic politicians, administrators and more importantly humans.

Lecture 3: The logic and magic of Sanskrit

Dr Sampadananda Mishra, a renowned Sanskrit scholar whose work is focused towards rediscovering the aesthetic and scientific nature of the Sanskrit language delivered the third lecture titled 'The Logic and Magic of Sanskrit' on 1st February. Sampananda Mishra based in Puducherry, is the Director of the Sri Aurobindo Foundation for Indian Culture. His interests in Sanskrit go beyond merely academic.

Sanskrit has been an integral part of our heritage and gives one access to a vast literature comprising epics, poems and texts related to various sciences. In modern times however, this language has been removed from the consciousness of public. Sampadananda Mishra endeavours to change this.

He has worked extensively to popularise Sanskrit and inspire awe amongst people, especially children, about its structure and versatility. He explained to us how words in Sanskrit are created out of sounds, intuitively. This is in stark contrast to a language like English where words are, more often than not, unrelated to the objects they describe. Sampadananda Mishra described to us how he has used Sanskrit shlokas to correct speech deficiencies in children. For the scientifically inclined however, an awe inspiring moment was when he spoke about the chess knight problem, a mathematical problem that remained unsolved for long in western civilization until the mathematician Leonhard Euler solved it. This problem however was solved much earlier in India, as evidenced by the existence of an entire genre of poetry in Sanskrit called *"turagapadabandha"* (arrangement in the steps of a horse), which gives the solution in the form of a verse.

During the subsequent interaction session, he elaborated upon the techniques he had developed to make learning Sanskrit a fun and easy activity. He also elaborated upon his efforts towards creating a database on Sanskrit literature catering exclusively for children. Sampadananda Mishra's talk and the subsequent interaction ignited a new found interest and passion for Sanskrit in many at RRI.

(Top) Shanti Pappu, Harsh Mander and Sampadananda Mishra; (Bottom)during the informal discussion session at the Library.

Visit of the Director, German Research Foundation (DFG) to RRI

Matthias Kiesselbach, Director DFG (German Research Foundation) India office visited Raman Research Institute on 11th December 2018. The aim of the visit was to promote Indo-German scientific collaboration through interactions between RRI members and German peers;

opportunities arising from various DFG funding calls for collaborative research projects as well as upcoming joint calls with Indian funding agencies were discussed. After Sanjukta Roy (LAMP) received a communication from the DFG India office conveying the interest of Matthias Kiesselbach to visit RRI, K S Dwarakanath (AA) helped in organising the meeting with the representatives of all the research groups in RRI.

After Matthias Kiesselbach arrived at RRI, there was still some time before the meeting was scheduled to start thus providing an ideal opportunity for a tour of the RRI campus. He was delighted to see the beautiful RRI campus and the legacy of Sir C. V. Raman.

The meeting took place in the Council room (main building) at 3:00 pm. Apart from Matthias Kiesselbach, the meeting was attended by K S Dwarakanath (AA), Nayantara Gupta (AA), Sadiq Rangwala (LAMP), Pratibha R (SCM), Dibyendu Roy (TP) and Sanjukta Roy (LAMP). In the beginning of the meeting, representatives from each of the research groups gave an overview of the various ongoing research in their respective groups. Thereafter, Matthais Kiesselbach gave a detailed presentation describing the various avenues of DFG funding for bilateral Indo-German collaborative research projects, short-term research visits to Germany, organization of Indo-German joint workshops, various fellowships for doctoral programmes and post-doctoral research in Germany, Mercator fellowships, joint calls with Indian funding agencies and excellence programmes such as Emmy Noether programme and Heisenberg fellowships and professorships. He highlighted the importance of scientific collaboration with India for the progress of science and research in Germany, which had motivated the establishment of the DFG India office in New Delhi. The presentation was very interactive and the speaker gave detailed answers to all our queries regarding the various funding possibilities and the procedures to avail them. He shared the contact details of the DFG India office (New Delhi) for direct communication by RRI members. He also gave several sets of information booklets describing the various steps taken by the German Research Foundation for promotion of science and research. These booklets contain all the information given by him during his presentation as well as guidelines for preparation of proposals for collaborative research projects and are available with the secretary of the respective research groups at RRI for reference. At the end of the meeting, as a token of goodwill, Matthias Kiesselbach presented a souvenir, which was accepted on behalf of RRI by K S Dwarakanath.

In conclusion, it was a very fruitful visit that could lead to long term bilateral scientific collaborations between research groups in RRI and Germany.

International Symposium in honour of Sir Anthony Leggett celebrating his 80th Birthday

Sir Anthony Leggett is one of the most celebrated physicists and deep thinkers of our time. The seminal ideas he had conceived led to the theory of the long-standing puzzling property of superfluidity of liquid helium which was subsequently experimentally vindicated. Strikingly, these ideas have found applications in diverse areas, from Quantum Physics to Cosmology, with even potential practical ramifications. For this discovery, he was awarded the Nobel Prize in 2003.

One of his other outstanding contributions has been to conceive ingenious ways of demonstrating intriguing fundamental features of quantum physics for large-scale objects, thereby pioneering studies involving a fascinating interplay between basic science and cutting-edge technology. On the other hand, his deep thoughts on the socio-cultural impact of science are widely revered.

Over the last few decades, Sir Anthony Leggett has been visiting India quite a number of times and has been interacting with a number of Indian physicists. In particular, his support and encouragement facilitated the setting up of the first dedicated photonic laboratory in India at RRI on studies related to Quantum Fundamentals and Frontier aspects of Quantum Communication and Computation.

Against the above backdrop, an International Symposium in honour of Sir Anthony Leggett celebrating his 80th birthday was held at RRI on 3rd and 4th February, 2019 with Urbasi Sinha (LAMP) as convenor and Dipankar Home of the Bose Institute as co-convenor. The talks at the symposium were given by speakers from India and abroad covering a variety of topics close to Sir Anthony's research interests including condensed matter physics as well as foundational aspects of quantum mechanics.

In view of the panoramic breadth of interests of Sir Anthony concerning different areas of physics reflected in his various writings that have provided insightful perspectives on the progress of physics, it was befitting to conclude the Symposium on 4th February evening with a Discussion Session entitled "Physics in the 21st Century: Open Questions and Future Directions". Deliberations of this session were initiated by Sir Leggett through his reflections on this topic, followed by contributions from the invited guests comprising a range of distinguished physicists attending this symposium, spanning different areas.

(Top) The symposium started with a cake cutting ceremony; (Bottom) group photo of the symposium participants with the RRI Main Building as a background.

RRI Cricket Tournament 2018-19

The RRI cricket tournament 2018-19 organized by third year PhD students commenced on 22nd December with six teams competing for the trophy. There were four student teams captained by Chandeshwar Misra (SCM), Saichand C (SCM), Jagadeesh R V (SCM) and Rishab Chatterjee (LAMP) whereas the other two teams were comprised of RRI members from gardening section captained by Sasikumar and the MES workshop captained by Ananda K. The group stage saw elimination of two teams and the remaining four went on to the play-off stage. After intense competition in the play-offs, Saichand's and Chandeswar's team went on to battle each other in the finals. Chandeshwar's team emerged as winners with Nomaan X bagging the man of the match award. G B Suresh (E&B) awarded the trophy to the winners.

(Left): Nomaan X (TP) getting ready to play the cover drive, with Sanjay Kumar Behara (SCM) in readiness to catch the ball if he misses or nicks behind (Right) Sayantan Majumdar (SCM) in his delivery stride; Marichandran (SCM) ensuring it is a legal delivery

National Science Day celebrations

The Institute celebrated National Science Day by opening its doors to students and general public. Over the course of the day the visitors were engaged in a variety of activities geared towards providing them a feel for the research areas and current research activities undertaken on a day-to-day basis at the Institute. The SCM group members interacted with the visitors via interactive demonstrations of the science concepts that form the basis for the research that is currently being pursued in their group. Additionally, posters were also displayed that discussed recent research results that eventuated from the group. A custom build 'dark room' was used to demonstrate how diffraction of light from an object could be used to understand its structure. Visits to the chemistry lab helped the students understand the procedure used to synthesize and characterize liquid crystals while visits to the LAMP group labs helped students get a peek into current research and the in-house built equipment being used at the Quantum Optics laboratory. The EEG group had on display the various components that were fabricated by them over the course of their technical support for the research activities of the four groups on campus while the MES gave live demonstration by fabricating various components using their CNC machine and lathe. Students stopping at the library were treated to posters containing photographs of Raman depicting various milestones in his life. Library members were eager to share the historical significance of these photos and were seen engaged in conversation with interested students. Lunch was provided to the visitors and the day's activities concluded with visits to the Raman museum.

A collage of images from National Science Day 2019 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

Academic Staff

Astronomy and Astrophysics

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N Udaya Shankar (Emeritus Scientist) from 1.5.2018
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Gunashekar

C Haridas – till 28.2.2019

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K Palani

M Rajagopal

K G Narasimhalu

M Ramesh

M Gopinath

Jayamma

C Lakshmamma

T Murali

Narayana

V Venkatesh

Varalakshmi

C Elumalai

A Ramanna

Lingegowda – till 30.4.2018

D Mahalinga

Mailarappa

Marappa

S Muniraju – till 31.1.2019

Rangalakshmi

D Krishna

T Mahadeva

C Sampath

S Sridhar

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Matadeen (Security In-charge)

H Vaderappa

BM Basavarajaiah

UA Earappa

H Gangaiah

Keshavamurthy

Suresha

K Krishnappa

K Pushparaj

OM Ramachandra

G Ramakrishna

M Sannaiah

Transport

M Balarama

CK Mohanan

G Prakash

Rahamath Pasha

G Raja

M Venkateshappa

Canteen & Guest House

N Narayanappa (Consultant)

K. Velayutham

Shivamallu

Mangala Singh

Muniratna

T Naganna

DB Padmavathy

PC Prabhakar

N Puttaswamy

Uma – till 31.3.2019

Sharadamma

Gauribidanur

Papanna – till 31.5.2018

RP Ramji Naik

NR Srinath

Medical Consultants

Dr. BV Sanjay Rao

Dr. PH Prasad

Dr. N Sundari

Publications

Appendix - I

Papers In Journals

1. Anisamide-Anchored Lyotropic Nano-Liquid Crystalline Particles with AIE Effect: A Smart Optical Beacon for Tumor Imaging and Therapy
Urandur, Sandeep*; Banala, Venkatesh Teja*; Pratibha, R + 8 Co-Authors
ACS Applied Materials & Interfaces, 2018, Vol.10, p12960

2. Supernova explosions of massive stars and cosmic rays
Biermann, P L*; Nath, Biman B; + 12 Co-Authors
Advances in Space Research, 2018, Vol.62, p27733

3. Airy wavepackets are Parelmovov coherent states
Vyas, Vivek M
American Journal of Physics, 2018, Vol.86, p750

4. The Quantum Cheshire Cat effect: Theoretical basis and observational implications
Duprey, Q*; Kanjilal, S*; Sinha, Urbasi; Home, D*; Matzkin, A*
Annals of Physics, 2018, Vol.391, p1

5. Boundaries without boundaries
Facchi, Paolo*; Garnero, Giancarlo*; Marmo, Giuseppe*; Samuel, J; Sinha, Supurna
Annals of Physics, 2018, Vol.394, p139

6. Lorentzian geometry for detecting qubit entanglement
Samuel, J; Shivam, Kumar; Sinha, Supurna
Annals of Physics, 2018, Vol.396, p159

7. Rotation measurements using a resonant fiber optic gyroscope based on Kagome fiber
Ravaille, Alexia*; Feugnet, Gilles*; Debord, Benoit* and Bretenaker, Fabien+
Applied Optics, 2019, Vol.58, p2198

8. Study of Ga+ implantation in Si diodes: effect on optoelectronic properties using micro-spectroscopy
Deshpande, Preeti*; Vilayurganapathy, Subramanian + 2 Co-Authors
Applied Physics A-Materials Science & Processing, 2018, Vol.125, Article Number: 181

9. Nonlinear optical properties of lead-free ferroelectric nanostructured perovskite
Sadhu, Sai Pavan Prashanth*; Thomas, Anitta Rose; Philip, Reji + 4 Co-Authors
Applied Physics B: Lasers and Optics, 2018, Vol. 124, p200

10. Usage of Electronic Resources by the Research Scholars of REVA University: A Study
Vasantha B* ; Meera B M ; Dhanamjaya M*
Asian Journal of Information Science and Technology, 2018, Vol. 8, p71

11. A tale of two periods: determination of the orbital ephemeris of the super-Eddington pulsar NGC 7793 P13
Furst, F*; Walton, D J*; Rana, V + 10 Co-Authors
Astronomy & Astrophysics, 2018, Vol. 616, p A186

12. A two population electron synchrotron model for knots of extended jets
Mondal, Samaresh*; Gupta, Nayantara
Astroparticle Physics, 2019, Vol. 107, p15

13. Evolution of Intergalactic Gas in the Neighborhood of Dwarf Galaxies and Its Manifestations in the HI 21 cm Line
Vasiliev, Evgenii O.*; Ryabova, M V* ; Shchekinov, Yuri+; Sethi, S.K.
Astrophysical Bulletin, 2018, Vol.73, p401

14. SARAS 2 constraints on global 21-cm signals from the Epoch of Reionization
Singh, Saurabh; Subrahmanyan, Ravi; Udaya Shankar, N; Sathyanarayana Rao, Mayuri; Fialkov, Anastasia*; Cohen, Aviad*; Barkana, Rennan; Girish, B S; Raghunathan, A; Somashekar, R; Srivani, K S
Astrophysical Journal, 2018, Vol. 858, p54

15. Scintillation-based search for Off-pulse Radio Emission from Pulsars
Ravi, Kumar; Deshpande, A A
Astrophysical Journal, 2018, Vol. 859, p22

16. An Analytic Formulation of the 21cm Signal from the Early Phase of the Epoch of Reionization
Raste, Janakee; Sethi, S K
Astrophysical Journal, 2018, Vol. 860, p55

17. Effects of Thermonuclear X-Ray Bursts on Non-burst Emissions in the Soft State of 4U 1728-34
Bhattacharyya, Sudip*; Yadav, J S*; Paul, Biswajit + 8 Co-Authors
Astrophysical Journal, 2018, Vol. 860, p88

18. Comparing Redundant and Sky-model-based Interferometric Calibration: A First Look with Phase II of the MWA
LI, W*; Paul, Biswajit; Sethi, S K; Udaya Shankar, N; Subrahmanyan, Ravi; + 51 Co-Authors
Astrophysical Journal, 2018, Vol. 863, p170

19. Probing Star Formation in Galaxies at z ≈ 1 via a Giant Metrewave Radio Telescope Stacking Analysis
Apurba, Bera*; Nissim, Kanekar*; Benjamin, Weiner J*; Sethi, S K; Dwarakanath, K S
Astrophysical Journal, 2018, Vol. 865, p39

20. Observing the Influence of Growing Black Holes on the Pre-reionization IGM
Vasiliev, Evgenii O*; Sethi, S K; Shchekinov, Yuri+
Astrophysical Journal, 2018, Vol. 865, p130

21. Fermi-Large Area Telescope Observations of the Brightest Gamma-Ray Flare Ever Detected from CTA 102
Prince, Raj; Raman, Gayathri; Gupta, Nayantara + 2 Co-Authors
Astrophysical Journal, 2018, Vol. 866, p16

22. Assessment of Ionospheric Activity Tolerances for Epoch of Reionization Science with the Murchison Widefield Array
Trott, C M*; Sethi, S K; Udaya Shankar, N; Subrahmanyan, Ravi; + 19 Co-Authors
Astrophysical Journal, 2018, Vol. 867, p15

23. Stalling of Globular Cluster Orbits in Dwarf Galaxies
Kaur, Karamveer; Sridhar, S
Astrophysical Journal, 2018, Vol. 867, p134

24. Tidal Interactions and Mergers in Intermediate Redshift EDisCS Clusters
Deger, Sinan*; Rudnick, Gregory*; Kelkar, Kshitija
Astrophysical Journal, 2018, Vol. 869, p6

25. On the Geometry of Curvature Radiation and Implications for Subpulse Drifting
McSweeney, S J*; Bhat, N D R*; Tremblay, S E*; Deshpande, A A; Wright, G*
Astrophysical Journal, 2019, Vol. 870, p48

26. AGN Feedback in Galaxy Groups: A Detailed Study of X-Ray Features and Diffuse Radio Emission in IC 1262
Pandge, M B*; Sonkamble, S S*; Parekh, Viral + 4 Co-Authors
Astrophysical Journal, 2019, Vol. 870, p62

27. Multi-frequency Variability Study of Ton 599 during the High Activity of 2017
Prince, Raj
Astrophysical Journal, 2019, Vol. 871, p101

28. LAXPC/AstroSat Study of ~1 and ~2 mHz Quasi-periodic Oscillations in the Be/X-Ray Binary 4U 0115+63 during Its 2015 Outburst
Roy, Jayashree*; Agrawal, P C*; Paul, Biswajit; +13 Co-Authors
Astrophysical Journal, 2019, Vol. 872, p33

29. Dipole Anisotropy as an Essential Qualifier for the Monopole Component of the Cosmic-dawn Spectral Signature, and the Potential of Diurnal Pattern for Foreground Estimation
Deshpande, A A
Astrophysical Journal Letters, 2018, Vol.866, pL7

30. Heating of Intergalactic Gas Near Growing Black Holes During the Hydrogen Reionization Epoch
Vasiliev, Evgenii O.*; Shchekinov, Yuri+; Sethi, S.K.; Ryabova, M V*
Astrophysics, 2018, Vol.61, p354

31 Confronting phantom inflation with Planck data
Iqbal, Asif; Malik, Manzoor A*; Qureshi, Mussadiq H*
Astrophysics and Space Science, 2018, Vol 363, p222

32. Cytoskeletal Mechanisms of Axonal Contractility
Mutalik, Sampada P*; Joseph, Joby*; Pullarkat, Pramod A; Ghose, Aurnab*
Biophysical Journal, 2018, Vol.115, p713-724

33. Self-Assembled CNT-Polymer Hybrids in Single-Walled Carbon Nanotubes Dispersed Aqueous Triblock Copolymer Solutions
Vijayaraghavan D; Manjunatha A S; Poojitha C G
Brazilian Journal of Physics, 2018, Vol.48, p130

34. Multifunctional nitrogen sulfur co-doped reduced graphene oxide - Ag nano hybrids (sphere, cube and wire) for nonlinear optical and SERS applications
Nair, Anju K*; Bhavitha, K B*; Perumbilavil, Sreekanth*; Sankar, Pranitha
Carbon, 2018, Vol.132, p380

35. Charge Transport in Novel Phenazine Fused Triphenylene Supramolecular Systems
Gowda, Ashwathanarayana; Jacob, Litwin; Singh, Dharmendra Pratap*; Douali, Redouane*; Kumar, Sandeep
Chemistry Select, 2018, Vol.3, p6551

36. Supramolecular Self-Assembly of Ionic Discotic Liquid Crystalline Dimer with DNA at Interfaces
Mallik, Samapika*; Nayak, Alpana*; Daschakraborty, Snehasis*; Kumar, Sandeep; Suresh, K A*
Chemistry Select, 2018, Vol.3, p7318

37. Novel Annulated Triphenylene Discotic Liquid Crystals Generated by Pictet-Spengler Cyclization
Vadivel, Marichandran; Siva Kumar, Irla; Swamynathan, K; Raghunathan, V A; Kumar, Sandeep
Chemistry Select, 2018, Vol.3, p8763

38. Periodic Grating-like Patterns Induced by Self-Assembly of Gelator Fibres in Nematic Gels
Topnani, Neha B; Prutha, N; Pratibha, R
ChemPhysChem, 2018, Vol.19, p1471

39. From Euclidean to Lorentzian Loop Quantum Gravity via a Positive Complexifier
Varadarajan, Madhavan
Classical and Quantum Gravity, 2019, Vol. 36, p015016

40. Platinum nanoparticles–decorated graphene-modified glassy carbon electrode toward the electrochemical determination of ascorbic acid, dopamine, and paracetamol
Anupam Kumar, Manne*; Lakshminarayanan, V; Ramamurthy, Sai Sathish*
Comptes Rendus Chimie, 2019, Vol. 484, p81

41. Synthesis, mesomorphic properties and nonlinear optical studies of alkyl and alkoxy phenylacetylene containing phenazine fused extended triphenylene discotic liquid crystalline dyes
Gowda, Ashwathanarayana; Jacob, Litwin; Patra, Alakananda; George, Agnes; Philip, Reji; Kumar, Sandeep
Dyes and Pigments, 2019, Vol. 160, p128

42. Institutional Repository Know-how of a decade in Managing Digital Assets
Meera, B M; Krishnamurthy, S; Kaddipujar, Manjunath
EPJ Web of Conferences, 2018, Vol. 186, p07001

43. An image-processing method to detect sub-optical features based on understanding noise in intensity measurements
Bhatia, Tripta
European Biophysics Journal, 2018, Vol.47, p531

44. Simple analytical model of a thermal diode
Kaushik, Saurabh; Kaushik, Sachin*; Rahul, Marathe*
European Physical Journal B, 2018, Vol.91, p87

45. SARAS 2: a spectral radiometer for probing cosmic dawn and the epoch of reionization through detection of the global 21-cm signal
Singh, Saurabh; Subrahmanyan, Ravi; Udaya Shankar, N; Sathyanarayana Rao, Mayuri; Girish, B S; Raghunathan, A; Somashekar R; Srivani K S
Experimental Astronomy, 2018, Vol. 45, p269

46. Liquid Crystals Decorated Gold Nanoparticles for the Photoswitching Properties
Rahman, Md. Luftor *; Yuvaraj, A R; Kumar, Sandeep + 3 Co-Authors
General Chemistry, 2018, Vol.4, p180009

47. Entropy and geometry of quantum states
Shivam, Kumar; Reddy, Anirudh; Samuel, J; Sinha, Supurna
International Journal of Quantum Information, 2018, Vol.16, p1850032

48 Iridium Satellite Signals: A Case Study in Interference Characterization and Mitigation for Radio Astronomy Observations
Deshpande, A A; Lewis B M*
Journal of Astronomical Instrumentation, 2019, Vol.8, p1940009

49. The dynamic spectral signatures from lunar occultation: A simulation study
Patel, Jigisha V; Deshpande A A
Journal of Astrophysics and Astronomy, 2019, Vol. 40, p3

50. Salt-induced swelling transitions of a lamellar amphiphile-Polyelectrolyte complex
Thomas, Meera; Swamynathan K; Raghunathan V A
Journal of Chemical Physics, 2019, Vol.150, p094903

51. Constraining the halo size from possible density profiles of hydrogen gas of Milky Way Galaxy
Biswas, Sayan; Gupta, Nayantara
Journal of Cosmology and Astroparticle Physics, 2018, Vol. 07, p063

52. Hydrogen bond-driven columnar self-assembly of electroluminescent D-A-D configured cyanopyridones
Vinayakumara D R*; Ulla, Hidayath*; Kumar, Sandeep + 5 Co-Authors
Journal of Materials Chemistry C, 2018, Vol.6, p7385

53. Studies on growth and characterization of (E)-N'-[4-(dimethylamino) benzylidene]-4-hydroxybenzohydrazide hemihydrate: a nonlinear optical material

Subashini, A*; Priyadharsani, Poornima*; Rose, P; Philip, R + 5 Co-Authors
Journal of Materials Science: Materials in Electronics, 2019, Vol.30, p2638

54. Lyotropic liquid crystals of CdS nanoribbons
Avinash B S; Kumar, Manish; Kumar, Sandeep
Journal of Molecular Liquids, 2018, Vol.264, p352

55. Dependence of physical parameters on the size of silver nano particles forming composites with a nematic liquid crystalline material
Tripathi, Pratibha*; Mishra, Mukesh*; Kumar, Sandeep + 2 Co-Authors
Journal of Molecular Liquids, 2018, Vol.268, p403

56. Novel electron-deficient phenanthridine based discotic liquid crystals
Yuvaraj, A R; Renjith, Anu; Kumar, Sandeep
Journal of Molecular Liquids, 2018, Vol.272, p583

57. Supramolecular columnar self-assembly of wedge-shaped rhodanine based dyes: Synthesis and optoelectronic properties
Vinayakumara D R*; Kumar, Sandeep; Adhikari, A V*
Journal of Molecular Liquids, 2019, Vol.274, p215

58. Self-assembly of Taper- and Wedge-Shaped Maleimide Derivatives: Synthesis and Structure-property Relationship
Adhikari, A V *; Kumar, Sandeep; Vinayakumara, D R * & Krishna Prasad, S *
Journal of Molecular Liquids, 2019, Vol.284, p765

59. Synthesis, characterization, crystal structure and liquid crystal studies of some symmetric naphthalene derivative molecules
Srinivasa, H T; Palakshamurthy B S*; Devarajegowda H C*; Hariprasad S*
Journal of Molecular Structure, 2018, Vol.1173, p620

60. Microscale Structures Arising from Nanoscale Inhomogeneities in Nematics Made of Bent-Shaped Molecules
Krishnamurthy, Kanakapura S*; Kanakala, M B*; Yelamaggad, C V*; Madhusudana, N V
Journal of Physical Chemistry B, 2019, Vol.123, p1423

61. Electron-Transfer Studies of Model Redox-Active Species (Cationic, Anionic, and Neutral) in Deep Eutectic Solvents
Renjith, Anu; Lakshminarayanan, V
Journal of Physical Chemistry C, 2018, Vol.122, p25411

62. Extreme statistics and index distribution in the classical 1d Coulomb gas
Dhar, Abhishek*; Kundu, Anupam*; Sabhapandit, Sanjib + 2 Co-Authors
Journal of Physics A: Mathematical and Theoretical, 2018, Vol.51, p295001

63. Pulse width dependent dynamics of laser-induced plasma from a Ni thin film
Thomas, Jinto*; Joshi, Hem Chandra*; Kumar, Ajai*; Philip, Reji
Journal of Physics D: Applied Physics, 2019, Vol.52, p135201

64. Generation of large-scale magnetic fields due to fluctuating in shearing systems
Jingade, Naveen; Singh, Nishant K*; Sridhar, S
Journal of Plasma Physics 2018, Vol. 84, 735840601

65. Steady state, relaxation and first-passage properties of a run-and-tumble particle in one-dimension
Malakar, Kanaya*; Jemseena, V* Sabhapandit, Sanjib + 5 Co-Authors
Journal of Statistical Mechanics: Theory and Experiment, 2018, p043215

66. Partial entropy production in heat transport
Gupta, Deepak; Sabhapandit, Sanjib
Journal of Statistical Mechanics: Theory and Experiment, 2018, p063203

67. Exact distribution for work and stochastic efficiency of an isothermal machine
Gupta, Deepak
Journal of Statistical Mechanics: Theory and Experiment, 2018, p073201

68. Stochastic resetting in underdamped Brownian motion
Gupta, Deepak
Journal of Statistical Mechanics: Theory and Experiment, 2019, p 033212

69. Femtosecond supercontinuum generation in scattering media
Ramachandran, Hema; Dharmadhikari, J A*; Dharmadhikari, A K*
Journal of the Optical Society of America B, 2019, Vol. 36, pA38

70. Preparation, spectral and thermal properties of new Isoflavone derivatives: mesomorphic properties and DFT studies
Mohammad, AbdulKarim-Talaq*; Alwari, Rusul Yousif*; Srinivasa, H T + 2 Co-Authors
Liquid Crystals, 2018, Vol.45, p1699

71. CdSe quantum dots in chiral smectic C matrix: experimental evidence of smectic layer distortion by small and wide angle X-ray scattering and subsequent effect on elector-optical parameters
Singh, D P*; Duncan, A E*; Kumar, Sandeep + 6 Co-Authors
Liquid Crystals, 2019 Vol.46, p376

72. Scholl reaction of hexaphenylbenzenes with hexakis-alkoxy substituents
Setia, Shilpa*; Kumar, Sandeep; Adhikari, Debashis*; Pal, Santanu Kumar*
Liquid Crystals, 2019, Vol.46, p430

73. New fluorescent columnar mesogens derived from phenanthrene–cyanopyridone hybrids for OLED applications
Vinayakumara, D R*; Ulla, Hidayath*; Kumar, Sandeep + 2 Co-Authors
Materials Chemistry Frontiers, 2018, Vol.2, p2297

74. Carbon paste modified with Bi decorated multi-walled carbon nanotubes and CTAB as a sensitive voltammetric sensor for the detection of Caffeic acid
Erady, Veera*; Mascarenhas, Ronald J*; Dhason, A + 3 Co-Authors
Microchemical Journal, 2019, Vol.146, p73

75. Extraplanar X-ray emission from disc-wide out ows in spiral galaxies.
Vijayan, Aditi; Sarkar, Kartick Chandra; Nath, Biman B; Sharma, Prateek*; Shchekinov, Yuri+
Monthly Notices of the Royal Astronomical Society, 2018, Vol. 475, p5513

76. Measuring the masses of Intermediate Polars with NuSTAR: V709 Cas, NY Lup and V1223 Sgr
Shaw, A W*; Heinke, C O*; Rana, V + 3 Co-Authors
Monthly Notices of the Royal Astronomical Society, 2018, Vol. 476; p554

77. Secular instabilities of Keplerian stellar discs
Kaur, Karamveer; Kazandjian, Mher V*; Sridhar, S; Touma, Jihad R*
Monthly Notices of the Royal Astronomical Society, 2018, Vol. 476; p4104

78. Deformation of the Galactic Centre stellar cusp due to the gravity of a growing gas disc
Kaur, Karamveer; Sridhar, S
Monthly Notices of the Royal Astronomical Society, 2018, Vol. 477; p112

79. Twin radio relics in a near-by low-mass galaxy cluster Abell 168
Dwarakanath, K S; Parekh, Viral; Kale, Ruta*; George, Lijo
Monthly Notices of the Royal Astronomical Society, 2018, Vol. 477; p957

80. Observation of variable pre-eclipse dips and disc winds in the eclipsing LMXB XTE J1710-281
Raman, Gayathri; Maitra, Chandreyee*; Paul, Biswajit
Monthly Notices of the Royal Astronomical Society, 2018, Vol. 477, p5358

81. X-ray and SZ constraints on the properties of hot CGM
Singh, Priyanka; Majumdar, Subhabrata*; Nath, Biman B; Silk, Joseph*
Monthly Notices of the Royal Astronomical Society, 2018, Vol. 478, p2909

82. Cosmic ray heating of intergalactic medium: patchy or uniform?
Jana, Ranita; Nath, Biman B
Monthly Notices of the Royal Astronomical Society, 2018, Vol. 479, p153–161

83. Galactic synchrotron distribution derived from 152 H II region absorption features in the full GLEAM survey
Su, H*; Dwarakanath, K S; + 21 Co-Authors
Monthly Notices of the Royal Astronomical Society, 2018, Vol. 479, p 4041

84. Constraining cosmic ray acceleration in young star clusters using multi-wavelength observations
Gupta, Siddhartha; Nath, Biman B; Sharma, Prateek*
Monthly Notices of the Royal Astronomical Society, 2018, Vol. 479; p5220

85. A multifrequency radio continuum study of the Magellanic Clouds – I. Overall structure and star formation rates
For, B Q*; Deshpande, A A; Dwarakanath, K S; Udaya Shankar, N ; Srivani, K S; Subrahmanyan, Ravi; Prabu, T; + 39 Co-Authors
Monthly Notices of the Royal Astronomical Society, 2018, Vol. 480, p2743

86. A study of spectral curvature in the radio relic in Abell 4038 using the uGMRT
Kale, Ruta*; Parekh, Viral; Dwarakanath, K S
Monthly Notices of the Royal Astronomical Society, 2018, Vol. 480, p5352

87. Hard X-ray-selected giant radio galaxies – I. The X-ray properties and radio connection
Ursini, F*; Bassani, L*; Panessa, F*; Bird, A J*; Bruni, G*; Fiocchi, M*; Malizia, A*; Saripalli, Lakshmi; Ubertini P*
Monthly Notices of the Royal Astronomical Society, 2018, Vol. 481, p4250

88. Spectral properties of MXB 1658–298 in the low/hard and high/soft state
Sharma, Rahul*; Jaleel, Abdul*; Jain, Chetana*; Pandey, Jeewan C*; Paul, Biswajit; Dutta, Anjan*
Monthly Notices of the Royal Astronomical Society, 2018, Vol. 481, p5560

89. The Murchison Widefield Array Transients Survey (MWATS). A search for low-frequency variability in a bright Southern hemisphere sample
Bell, M E*; Deshpande, A A; Prabu, T; Udaya Shankar, N; Srivani, K S; Subrahmanyan, Ravi; + 35 Co-Authors
Monthly Notices of the Royal Astronomical Society, 2018, Vol.482, p2484

90. Thermonuclear X-ray bursts in rapid succession in 4U 1636-536 with AstroSat-LAXPC
Beri, Aru; Paul, Biswajit; Varun; + 12 Co-Authors
Monthly Notices of the Royal Astronomical Society, 2018, Vol. 482, p4397

91. Radio background and IGM heating due to Pop III supernova explosions
Jana, Ranita; Nath, Biman B; Biermann P*
Monthly Notices of the Royal Astronomical Society, 2019, Vol. 483, p5329

92. Multitude of iron lines including a Compton-scattered component in OAO 1657 - 415 detected with Chandra
Pradhan, Pragati*; Raman, Gayathri; Paul, Biswajit
Monthly Notices of the Royal Astronomical Society, 2019, Vol. 483, p5687

93. Correlations of the feedback energy and BCG radio luminosity in galaxy clusters
Iqbal, Asif; Kale, Ruta*; Nath, Biman B.; Majumdar, Subhabrata*
Monthly Notices of the Royal Astronomical Society Letters, 2018, Vol. 480, pL68

94. Detection of a cyclotron line in SXP 15.3 during its 2017 outburst
Maitra, Chandreyee*; Paul, Biswajit; Haberl, F*; Vasilopoulos, G*
Monthly Notices of the Royal Astronomical Society Letters, 2018, Vol. 480, pL136

95. Probing the Cyclotron line characteristics of 4U 1538-522 using AstroSat-LAXPC
Varun; Maitra, Chandreyee*; Pradhan, Pragati*; Raichur, Harsha*; Paul, Biswajit
Monthly Notices of Royal Astronomical Society, 2019, Vol. 484, pL1

96. Mechanochemical feedback control of dynamin independent endocytosis modulates membrane tension in adherent cells
Thottacherry, Joseph Jose*; Kumar, Amit*; Pullarkat, Pramod A; + 15 Authors
Nature Communications, 2018, Vol. 9, Article Number 4217

97. Optoelectronic exploration of novel non-symmetrical star-shaped discotic liquid crystals based on cyanopyridine
Vinayakumara, D R*; Swamynathan, K; Kumar, Sandeep; Adhikari, A V*
New Journal of Chemistry, 2018, Vol. 42, p16999

98. Novel phenazine fused triphenylene discotic liquid crystals: synthesis, characterisation, thermal, optical and nonlinear optical properties
Gowda, Ashwathanarayana; Jacob, Litwin; Joy, Nithin; Philip, Reji; Kumar, Sandeep
New Journal of Chemistry, 2018, Vol. 42, p19034

99. Measuring the deviation from the superposition principle in interference experiments
Rengaraj, G; Prathwiraj, U; Sahoo, Surya Narayan; Somashekar, R; Sinha, Urbasi
New Journal of Physics, 2018, Vol.20, p63049

100. Phase sensitive amplification enabled by coherent population trapping
Neveu, P*; Banerjee, C*; Lugani, J*; Bretenaker, Fabien+ + 2 Co-Authors
New Journal of Physics, 2018, Vol. 20, p83043

101. Theoretical and experimental approach to the investigation of hyperpolarizability and charge transfer characteristics of NLO active 2',3,4,4',5-pentamethoxy chalcone with silver atoms adsorbed
John, Jerin Susan*; Sajana, D*; Chandrabhas, N*; Nithin, Joy; Philip, Reji
Optical Materials, 2018, Vol.84, p409

102. Conditional entropic uncertainty and quantum correlations
Karthik, H S; Devi, Usha A R*; Tej, Prabhu J*; Rajagopal, A K*
Optics Communications, 2018, Vol.427, p 635

103. Fully–correlated multi–mode pumping for low–noise dual–frequency VECSELs
Gredat, Grégory*; Chatterjee, Debanuj*; Bretenaker + 5 Co-Authors
Optics Express, 2018, Vol. 26, p26217

104. Measurements of spin properties of atomic systems in and out of equilibrium via noise spectroscopy
Swar, Maheswar; Roy, Dibyendu; Dhanalakshmi, D; Chaudhuri, Saptarishi; Roy, Sanjukta; Ramachandran, Hema
Optics Express, 2018, Vol. 26, p 32168

105. Infrared laser threshold magnetometry with a NV doped diamond intracavity etalon
Dumeige, Yannick*; Roch, Jean-François*; Bretenaker, Fabien^{+} + 8 Co-Authors
Optics Express, 2019, Vol. 27, p1706

106. Phase evolution of the direct detection noise figure of a nondegenerate fiber phase-sensitive amplifier
Labidi, Tarek*; Fsaifes, Ihsan*; Bretenaker, Fabien^{+} + 2 Co-Authors
Optics Letters, 2018, Vol.43, p4546

107. Coherent microwave-to-optical conversion by three-wave mixing in a room temperature atomic system
Adwaith, K V; Asha K; Manwatkar, Charudatta*; Bretenaker, Fabien^{+}; Narayanan, Andal
Optics Letters, 2019, Vol.44, p33

108. Spatially correlated photonic qutrit pairs using pump beam modulation technique
Ghosh, Debadrita; Jennewein, Thomas*; Kolenderski, Piotr*; Sinha, Urbasi
OSA Continuum, 2018, Vol.1, p996

109. Quantum Brownian motion in a magnetic field: Transition from monotonic to oscillatory behavior
Satpathi, Urbashi;, Sinha Supurna
Physica A, 2018, Vol.506, p692

110. Modeling cell-substrate de-adhesion dynamics under fluid shear
Renu, Maan*; Garima, Rani*; Gautam, Menon I*; Pullarkat, Pramod A
Physical Biology, 2018, Vol.15, P 046006

111. Cooling of trapped ions by resonant charge exchange
Dutta, Sourav; Rangwala, S A
Physical Review A, 2018, Vol.97, p041401

112. Detection of ultracold molecules using an optical cavity
Sawant, Rahul; Dulieu, Olivier*; Rangwala, S A
Physical Review A, 2018, Vol.97, p063405

113. Excitation and propagation of surface polaritonic rogue waves and breathers
Asgarnezhad-Zorgabad, Saeid*; Sadighi-Bonabi, Rasoul*; Sanders, Barry C
Physical Review A, 2018, Vol.98, p013825

114. Light propagation through one-dimensional interacting open quantum systems
Manasi, Pooja; Roy, Dibyendu
Physical Review A, 2018, Vol. 98, p023802

115. Measuring average of non-Hermitian operator with weak value in a Mach-Zehnder interferometer
Nirala, Gaurav*; Sahoo, Surya Narayan; Pati, Arun K*; Sinha, Urbasi
Physical Review A, 2019, Vol. 99, p022111

116. 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, p033617

117. Constraint algebra in Smolins' G→0 limit of 4D Euclidean gravity
Varadarajan, Madhavan
Physical Review D, 2018, Vol. 97, p106007

118. Statistics of overtake events by a tagged agent
Das, Santanu; Dhar, Deepak*; Sabhapandit, Sanjib
Physical Review E, 2018, Vol. 98, p052122

119. Interacting passive advective scalars in an active medium
Hossein, Raj S K; Mandal, Rituparno*; Rao, Madan*
Physical Review E, 2018, Vol. 98, p052608

120. Active Brownian Motion in Two Dimensions
Basu, Urna; Majumdar, Satya N*; Rosso, Alberto*; Schehr, Gregory*
Physical Review E, 2018, Vol. 98, p062121

121. Run-and-tumble particle in one-dimensional confining potential: Steady state, relaxation and first passage properties
Dhar, Abhishek*; Kundu, Anupam*; Sabhapandit, Sanjib + 2 Co-Authors
Physical Review E, 2019, Vol. 99, p032132

122. Kinetic Spinodal Instabilities in the Mott Transition in V2O3: Evidence from Hysteresis Scaling and Dissipative Phase Ordering
Bar, Tapas*; Choudhary, Sujeet Kumar*; Ashraf, Md. Arsalan + 3 Co-Authors
Physical Review Letters, 2018, Vol. 121, Article Number: 045701

123. Enhancement of optical emission and ion currents in a laser produced silicon plasma by femtosecond laser-induced periodic surface structuring
Anoop, K K; Verma, Nancy; Joy, Nithin; Harilal, S S *; Philip, Reji
Physics of Plasmas, 2018, Vol. 25, p063304

124. Time-resolved optical emission spectroscopic studies of picosecond laser produced Cr plasma
Rao, Kavya H*; Smijesh, N*; Klemke, N*; Philip, Reji + 2 Co-Authors
Physics of Plasmas, 2018, Vol. 25, p063505

125. Effect of ambient gas pressure on nanosecond laser produced plasma on nickel thin film in a forward ablation geometry
Thomas, Jinto*; Joshi, Hem Chandra*; Kumar, Ajai*; Philip, Reji
Physics of Plasmas, 2018, Vol. 25, p103108

126. Effect of laser beam size on the dynamics of ultrashort laser-produced aluminum plasma in vacuum
Sankar, Pranitha; Shashikala H D*; Philip, Reji
Physics of Plasmas, 2019, Vol. 26, p013302

127. Transmitting a signal in negative time
Deo, P Singha*; Satpathi, Urbashi
Results in Physics, 2019, Vol.12, p1506

128. Physics and astrophysics of strong magnetic field systems with eXTP
Santangelo, Andrea*; Zane, Silvia*; Paul, Biswajit; + 36 Co-Authors
Science China Physics, Mechanics & Astronomy, 2019 Vol. 62, AR 029505

129. Observatory science with eXTP
Enrico, Bozzo*; JinLu, Qu*; Paul, Biswajit; + 152 Co-Authors
Science China Physics, Mechanics & Astronomy, 2019, Vol. 62, AR 29506

130. Electric field induced gelation in aqueous nanoclay suspensions
Gadige, Paramesh; Bandyopadhyay, Ranjini
Soft Matter, 2018, Vol.14, p 6974

Papers In Conference Proceedings

1. Step-wise potential development across the lipid bilayer under external electric fields
Majhi, Amit Kumar
62nd DAE Solid State Physics Symposium, 26–30 December 2017, Mumbai, India
AIP Conference Proceedings, 2018, Vol.1942, p040017-1

2. Building an efficient linear-array imager prototype
Balasubramanyam, R; Jois, Swaroop; Prakash, Ashwini
IEEE Radio and Antenna Days of the Indian Ocean (RADIO), Cape Town, 25th to 28th September 2017

3. Optical Spectroscopy of Spin Noise in alkali vapor
Swar, Maheswar ; Roy, Dibyendu ; Dhanalakshmi D ; Bhagyalakshmi D ; Chaudhuri, Saptarishi Roy, Sanjukta ; Ramachandran, Hema
International Conference on Molecular Spectroscopy Conference Proceedings, 8-10 December 2018

4. Digital Library Spectrum: Delve into Future
Meera, BM
Rethinking Libraries and Librarianship, Ed. by Babbar, Parveen; Kar, Debal C; Jain, P K; Paliwal, Geeta, 2019, p411
Proceedings of the ICoASL Conference 2019 held on 14-15 Feb 2019 at Institute of Economic Growth, New Delhi and Ambedkar University, New Delhi

5. Median filtering with very large windows: SKA algorithms for FPGAs
Sherwin, Tyrone*; Wang, Kevin I-Kai*; Prabu, T; & Sinnen, Oliver*
Proceedings of the 2015 IEEE-International Conference on Field-Programmable Logic and Applications held at Dublin, Ireland, 2018, p196

6. The Simons Observatory: instrument overview Nicholas
Galitzki, Nicholas*; Ali, Aamir*; Sathyanarayana Rao, Mayuri; +74 Co-Authors
Proceedings of Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy IX, edited by Jonas Zmuidzinas, Jian-Rong Gao
Proceedings of the SPIE, 2018, Vol. 10708, p1070804

7. Simons Observatory large aperture telescope receiver design overview
Zhu, Ningfeng*; Orlowski-Scherer*, John L*; Sathyanarayana Rao, Mayuri; + 33 Co-Authors

Proceedings of Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy IX, edited by Jonas Zmuidzinas, Jian-Rong Gao
Proceedings of the SPIE, 2018, Vol. 10708, p1070829-1

8. BoloCalc: a sensitivity calculator for the design of Simons Observatory
Hill, Charles A*; Bruno, Sarah Marie M*; Sathyanarayana Rao, Mayuri; + 34 Co-Authors
Proceedings of Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy IX, edited by Jonas Zmuidzinas, Jian-Rong Gao
Proceedings of the SPIE, 2018, Vol. 10708, p1070842-1

9. Electron beam induced modifications in third harmonic process of spray coated Mn: ZnO nanostructures
Antony, Albin*; Poomesh, P*; Philip, Reji; + 6 Co-Authors
SPIE OPTO, 2019, San Francisco, California, United States (02-07 Feb 2019)
Proceedings Volume 10919, Oxide-based Materials and Devices X, 2019, p1091924,

10. Early detection of breast cancer using ER specific novel NIR fluorescent dye conjugate : a phantom study using FD-FDOT system
Pillai, Vinay Jha*; Jose, Iven*; Ramachandran, Hema
SPIE BiOS, 2019, San Francisco, California, United States
Proceedings of the SPIE 10874, Optical Tomography and Spectroscopy of Tissue XIII, 2019, p1087410

Popular Articles

1. How Machilipatnam became site of a pioneering discovery in 19th century
Nath, B.B.
Indian Science Wire, Business Line, August 16, 2018

2. Gacheder somaj songshar
Nath, B.B.
Desh, August 2nd 2018

3. Striking the perfect equilibrium!: Supurna Sinha talks to Maria Cristina Marchetti
Sinha, Supurna
Resonance, Vol.24, March 2019, p393

4. Quantum frontiers and fundamentals: Meeting Report
Sinha, Urbasi
Current Science, 2018, Vol.115 (1), p15

In Press – Popular Articles

1. Jyamitir itahaser galicha – the woven history of geometry
Sinha, Supurna
Kalpabishwa, April 2019

Books Edited

1. Asundi, A Y and Meera B M, Ed: S R Ranganathans Classics – 1, The science and the profession of Libraries – A Visionary's perspective (A collection of 20 papers) – 125th Anniversary Commemoration volume, ESS Publications, New Delhi, 2018

Book Chapters

1. Stabilization of Discotic Liquid Crystals
Yuvaraj, A.R. & Kumar, Sandeep
In Polymer-modified Liquid Crystals, Chapter 15, Edited by Ingo Dierking, The Royal Society of Chemistry, 2019, p332

2. Nonlinear Optical Properties of Nanomaterials
Sankar, Pranitha & Philip, Reji
In Characterization of Nanomaterials: Advances and Key Technologies: Micro and Nano Technologies, Chapter 11, 2018, Pages 301-334

Miscellaneous

1. Elemental analysis of borosilicate, quartz, soda and lead glasses through energy dispersive X-ray analysis (EDX) method
Dhason, A
B.S.S.G. Journal, 2018, Vol.56, p123

2. Raman Research Institute
Meera B M
Sasthrakeralam, April 2018, p 44
(Malayalam Magazine)

Papers in Press – In Journals

1 Induced spatial geometry from causal structure
Eichhorn, Astrid*; Surya, Sumati; Versteegen, Fleur*
Classical and Quantum Gravity, 2019, Vol. 36, p105005

2 Measuring fluorescence into a nanofiber by observing field quadrature noise
Jalnapurkar, Shreyas*; Anderson, Paul*; Narayanan, Andal + 4 Co-Authors
Optics Letters, 2019, Vol.44, p1678

3. An MCS with iterative multi-dimensional Hamming product codes
Chandrasekaran, Parvathi; Balasubramanyam, R
IETE Journal of Research, published online October 2018, DOI:10.1080/03772063.2018.1527527

4. 3-Cyano thiophene-based π-conjugated mesogens: XRD and ^{13}C NMR investigations
Pratap, G*; Malkar, Deepshika; Roy, Arun + 3 Co-Authors
Liquid Crystals Today, 2019, Vol.46, p 680

5. Velocity distribution of driven granular gases
Prasad, V V*; Das, Dibyendu*; Sabhapandit, Sanjib ; Rajesh, R*
Journal of Statistical Mechanics: Theory and Experiment, 2019

6. Synergistic effect of hybrid Ce3+/Ce4+ doped Bi2O3 nano-sphere photocatalyst for enhanced photocatalytic degradation of alizarin red S dye and its NUV excited photoluminescence studies
Akshatha, S*; Sreenivasa, S*; Kumar, Sandeep; + 5 Co-Authors
Journal of Environmental Chemical Engineering, 2019, Vol. 77, p103053

7. Direct femtosecond laser fabricated photon sieve
Rodrigues, Vanessa R M *; Dharmadhikari, Jayashree A*; Ramachandran, Hema + 3 Co-Authors
OSA Continuum, 2019, Vol.2, p1328

8. X-ray scattering from a thickness modulated phase of lipid membranes
Madhukar, S; Raghunathan, V A
Journal of Applied Crystallography, 2019, Vol.52, 440

9. Methodical engineering of defects in MnXZn1-XO (x= 0.03, and 0.05) nanostructures by electron beam for nonlinear optical applications: A new insight
Antony, A*; Poomesh, P*; Philip, Reji; + 7 Co-Authors
Ceramics International, 2019, Vol. 45, p8988

10. Enhanced NLO activity of organic 2-methyl-5-nitroaniline crystal: Experimental and computational investigation with and without silver addition
John, Jerin Susan*; Sajan, D*; Prabukanthan, P*; Philip, Reji ; Joy, Nithin
Optics & Laser Technology, 2019, Vol. 113, p416

11. Influence of $MnCl_2$ on the properties of an amino acid complex single crystal-l-arginine perchlorate (LAPCl) for optical limiter applications
Thomas, Prince*; Junjuri, Rajendhar*; Joy, Nithin; Philip, Reji + 4 Co-Authors
Journal of Materials Science: Materials in Electronics, 2019, Vol. 30, p8407

12. Ultrahigh energy cosmic rays and neutrinos from light nuclei composition
Das, Saikat; Razzaque, Soebur* and Gupta, Nayantara
Physical Review D, 2019, Vol. 99, p083015

13. Alignment of liquid crystals using Langmuir-Blodgett films of unsymmetrical bent-core liquid crystals
Choudhary, Keerti*; Gupta, Raj Kumar*; Pratibha,R; Sadashiva, B K; Manjuladevi, V*
Liquid Crystals, Published online on 06 Feb 2019 https://doi.org/10.1080/02678292.2019.1574035

14. Photoluminescence and electrical conductivity measurement of liquid crystal doped with ZnO nanoparticles
Pushpavathi, N*; Sandhya, K L*; Pratibha, R
Liquid Crystals, 2019, Vol. 46, p666

Papers in Press – In Conference Proceedings

1. RRI Efficient linear-array imager: Salient aspects
Balasubramanyam, R
IEEE explore: 2019, URSI Asia-Pacific Radio Science Conference (AP-RASC)

2. Building a dedicated radio supernova search engine
Nair, Lekshmi M; Balasubramanyam, R
IEEE explore: 2019, URSI Asia-Pacific Radio Science Conference (AP-RASC)

Papers in Press – Book Chapter

1. Measurements of temporal fluctuations of magnetization in alkali vapour and applications
Swar, Maheswar; Roy, Dibyendu; D, Dhanalakshmi, D; Chaudhuri, Saptarishi; Roy, Sanjukta; Ramachandran, Hema
Emerging Trends in Advanced Spectroscopy, ed. by Weiman, Yang; Jibin, K P; Praveen, G L
Book Chapter, 2019, p

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

Conferences Attended & Institutions Visited

Appendix - II

Name	Conferences attended / Institutions visited	Title of paper/talk
Arun Roy	27th International Liquid Crystal Conference Kyoto International Conference Center, Japan 22 – 29 July 2018	Unusual smectic mesomorphism of bent core hockey stick shaped molecules
Arasi Sathyamurthy	Keysight Education Symposium Agilent Technologies, Bengaluru 24 September 2018	RF/microwave and digital applications
Avinash Deshpande	Homi Bhabha Centre for Science Education, Mumbai 26 – 27 April 2018	
	Curtin University, Australia 30 April – 19 May 2018	Sky Watch Network: A strategic initiative
	Workshop on Developing Astronomy Themed Experiments Inter University Centre for Astronomy & Astrophysics, Pune 18 – 20 June 2018	Radio astronomy related experiments *(Invited)*
	National Workshop on Exciting Applications of Electromagnetics SSN College of Engineering, Chennai 27 – 28 September 2018	Radio astronomy: Techniques and challenges *(Invited)*
	National Centre for Radio Astrophysics, Pune 23 – 24 November 2018	
	Homi Bhabha Center for Science Education Mumbai 29 October – 12 November 2018	
	Colloquium 'On Attempts to Detect EOR Global Signal and Swan' Indian Institute of Technology Kanpur Kanpur 31 January – 3 February 2019	Sky Watch Array Network: A strategic initiative
	National Institute of Technology Tiruchirapalli, Tamil Nadu 24 – 25 March 2019	Fascinating life-stories of cosmic light-houses

Name	Conferences attended / Institutions visited	Title of paper/talk
	Indian Institute of Technology Indore Indore 10 – 16 June 2018 16 – 20 July2018 05 – 11 September 2018 21 – 26 January 2019 17 – 21 February 2019	*12 lectures*
Biman Nath	Kendriya Vidyalaya, Bengaluru 20 July 2018 Workshop on Cosmology – The Next Decade International Centre for Theoretical Sciences Bengaluru 3 – 25 January 2019 Ashoka University, Haryana 13 February 2019	The moon *(2 lectures)* Diffuse matter in the universe: CGM to IGM *(Invited)* Who discovered helium in the sun?
Biswajit Paul	20th National Space Science Symposium Savitribai Phule Pune University, Pune 29 – 31 January 2019	The X-ray Polarimetry Mission XPoSat *(Plenary)*
Chandeshwar Misra	Bangalore School on Statistical Physics – IX International Centre for Theoretical Sciences Bengaluru 27 June – 13 July 2018 12th International Conference on Complex Fluids and Soft Matter Indian Institute of Technology, Roorkee 6 – 9 December 2018 Indo-US Workshop on Soft Matter Indian Institute of Technology, Roorkee 9 – 11 December 2018	An experimental study of the effects of the solvent microstructure on the aging and jamming dynamics of aqueous Laponite® suspensions
Dibyendu Roy	1st Workshop on Waveguide QED Centro Polivalente, Italy 4 - 8 June 2018 Joint Conclave of Monitoring-cum-Interaction Meet Hotel Marriot, Jaipur 8 – 10 June 2018	Dynamics of energy transfer in waveguide quantum electrodynamics systems Waveguide quantum electrodynamics

Name	Conferences attended / Institutions visited	Title of paper/talk
	Max Planck Institute for the Physics of Complex Systems, Germany 12 – 25 June 2018	
	Conference on Quantum Information and Many-Body Theory Indian Institute of Technology (BHU) Varanasi 1 – 3 March 2019	An open-quantum system description of Josephson effect in topological superconductors
	International Centre for Theoretical Sciences Bengaluru 12 March 2019	An open-quantum system description of Josephson effect in topological superconductors
Dwarakanath KS	Indian Institute of Astrophysics, Bengaluru 24 July 2018	Diffuse radio emission in galaxy clusters
	The Metre Wavelength Sky Conference - II National Centre for Radio Astrophysics Pune 18 – 22 March 2019	Diffuse radio emission in 'off-state' clusters
Gautam Vivek Soni	Founder's Day Celebration Poornaprajna Institute of Scientific Research Bengaluru 5 – 6 July 2018	Role of nanotechnology in structure-function relationship in biology *(Invited)*
	Annual Symposium Indian Institute of Science, Bengaluru 8 September 2018	Measuring molecular and cellular structures and the forces that control it *(Plenary)*
	Conference on Molecular Health – From Cell to Population Southern University of Science and Technology, China 3 – 4 November 2018	Measuring molecular and cellular structures and the forces that control it *(Invited)*
	Department of Science & Technology New Delhi 19 November 2018	
	GCE India P. Ltd., Bengaluru 31 January 2019	
	BioSCOPY Workshop Indian Institute of Science Education and Research, Kolkata 17 – 20 March 2019	

Name	Conferences attended / Institutions visited	Title of paper/talk
Gopala Krishna MR	Conference on Modern Engineering Trends in Astronomy 2018 National Centre for Radio Astrophysics Pune 14 – 15 September 2018	Signal processing electronics of POLIX-A Thomson X-ray Polarimeter
Jacob Rajan	Chief Information Security Officers – Deep Dive Training Programme Ministry of Electronics and Information Technology, Bengaluru 14 – 17 November 2018	
Jishnu Nambissan T	Conference on The Metre Wavelength Sky – II National Centre for Radio Astrophysics, Pune 18 – 22 March 2019	
Madhavan Varadarajan	Delhi University, Delhi 8 May 2018 Indian Institute of Technology, Delhi 14, 17 August 2018 Central University, Hyderabad 2 January 2019 30th Meeting of the Indian Association for General Relativity and Gravitation Birla Institute of Technology and Science Hyderabad, Hyderabad 3 – 5 January 2019	Introduction to Ashtekar variables a. Quantum gravity: A view from general relativity b. Exotic representations of QM and the Stone von Neumann Theorem Quantum gravity: A view from general relativity Loop quantum gravity *(Invited Plenary)*
Manjunath Kaddipujar	Author Workshop Raman Research Institute, Bengaluru 6 September 2018	
Meera BM	NCBS Monthly Talk on An Informal Conversation about the Caltech Archives National Centre for Biological Sciences Bengaluru 12 April 2018	

Name	Conferences attended / Institutions visited	Title of paper/talk
	NCBS Monthly Talk on Forgetting and Remembering: Oral History, Cultural Memory and the Postcolonial Archive National Centre for Biological Sciences Bengaluru 15 May 2018 Conference @ 'LIS Round Table with TCS' Hotel Gateway, Bengaluru 22 May 2018 Mini Symposium on Digitization – Securing the Books of Yesterday for Tomorrow Indian Academy of Sciences, Bengaluru 10 August 2018 Bangalore University, Bengaluru 20 August 2018 International Conference on Asian Special Libraries Institute of Economic Growth and Ambedkar University, New Delhi 14 – 16 February 2019 Capacity Building Workshop on Digital Archiving Indian Academy of Sciences, Bengaluru 22 February 2019 International Conference on Future of Libraries Indian Institute of Management, Bengaluru 26 – 29 February 2019	Digital library spectrum: Delve into Future *(Invited)*
Mugundhan V	Instrumentation Award Acceptance Presentation Indian Institute of Astrophysics, Bengaluru 3 August 2018	Long baseline interferometer observations of the meter wavelength solor corona
Nagaraj MN	Workshop on Strategies for Transforming Libraries: Growing Trends and Technologies PES University, Bengaluru 2 June 2018 Author Workshop Raman Research Institute, Bengaluru 6 September 2018	

Name	Conferences attended / Institutions visited	Title of paper/talk
Palak	Bangalore School on Statistical Physics – IX International Centre for Theoretical Sciences Bengaluru 27 June – 13 July 2018	
	12th International Conference on Complex Fluids and Soft Matter Indian Institute of Technology, Roorkee 6 – 9 December 2018	Study of instabilities at the interface of Newtonian and non-Newtonanian fluid in a quasi-two dimensional geometries
	Indo-US Workshop on Soft Matter Indian Institute of Technology, Roorkee 9 – 11 December 2018	
Prabu T	Conference on Modern Engineering Trends in Astronomy 2018 National Centre for Radio Astrophysics Pune 14 September 2018	A novel approach to the digital processing using the FPGAs for SKA pulsar search
	37th Meeting of Astronomical Society of India – SKA Workshop Christ University, Bengaluru 18 February 2019	a.Updates from the Square Kilometre Array India Technical Working Group b.Central signal processing-Contributions to the SKA CSP/PSS design
	The Metre Wavelength Sky Conference - II National Centre for Radio Astrophysics, Pune 18 – 22 March 2019	Fourier domain acceleration processing with FPGAs for the SKA pulsar research
Pramod Pullarkat	Science Academies Lecture Workshop on 'Soft Matter and Biological Physics' Maharani's College, Bengaluru 17 May 2018	Forces generation in living systems
	Unilever, Bengaluru 29 June 2018	Unique mechanical responses of axons of neuronal cells
	Powai Perspectives on Physics 2018 Symposium Indian Institute of Technology-Bombay Mumbai 12 – 13 October 2018	Mechanical responses of axons *(Invited)*
	Fluorescence Correlation Spectroscopy Meeting 2018 Jawaharlal Nehru University, New Delhi 15 – 17 November 2017	Mechanical responses of axons *(Invited)*

Name	Conferences attended / Institutions visited	Title of paper/talk
	International Centre for Theoretical Sciences Bengaluru 26 November 2018	Mechanical responses of cells
Raghavendra Rao KB	37th Meeting of Astronomical Society of India – SKA Workshop Christ University, Bengaluru 18 - 22 February 2019	
Raghunathan A	Conference on Modern Engineering Trends in Astronomy 2018 National Centre for Radio Astrophysics Pune 14 September 2018	Detection of epoch of recombination (ERA) signal: A potential application to set ultimate performance goals to future receiver systems
Raghunathan VA	Workshop on Soft Matter and Biological Physics Indian Academy of Sciences, Bengaluru 16 – 17 May 2018 Workshop on Physics of Materials Indian Academy of Sciences, Bengaluru 24 – 25 January 2019	Entropy in soft matter Soft matter
Rajkumar Biswas	Bangalore School on Statistical Physics – IX International Centre for Theoretical Sciences Bengaluru 27 June – 13 July 2018 12th International Conference on Complex Fluids and Soft Matter Indian Institute of Technology, Roorkee 6 – 9 December 2018 Indo-US Workshop on Soft Matter Indian Institute of Technology, Roorkee 9 – 11 December 2018	
Ramesh B	Space Applications Center, Ahmedabad 3 May 2018 2019 URSI Asia Pacific Radio Science Conference India Habitat Center, New Delhi 9 – 15 March 2019	a. RRI efficient linear-array imager b. Building a dedicated radio supernova search engine

Name		Title of paper/talk
Ranita Jana	Conference on Bubbles Big and Small Indian Institute of Science, Bengaluru 11 – 14 June 2018	
	Workshop on Cosmology – The Next Decade International Centre for Theoretical Sciences Bengaluru 3 – 25 January 2019	Radio background and IGM heating due to Pop III Supernova explosions
Ranjini Bandyopadhyay	Workshop on Soft Matter and Biological Physics Maharani Science College for Women Bengaluru 16 May 2018	The curious rheology of soft matter *(Invited)*
	Vigyan Jyoti Workshop Indian Institute of Technology, Mumbai 19 May 2018	The unusual flow of soft materials *(Invited)*
	Chetana Program Jawaharlal Nehru Centre for Advanced Scientific Research, Bengaluru 23 October 2018	Soft matters *(Invited)*
	International Conference on Complex and Functional Materials Biswa Bangla Convention Centre, Kolkata 13 – 16 December 2018	Electric field induced gelation of soft colloidal clay suspensions
	Faculty Development Program Ramaiah Institute of Technology, Bengaluru 28 January 2019	The flow and deformation *(rheology)* of soft matter *(Invited)*
	Indian Statistical Physics Community Meeting International Centre for Theoretical Sciences Bengaluru 15 February 2019	Experiments with active particles dispersed in a crowded environment of passive particles
Reji Philip	Faculty Development Programme on Applied Physics BMS Institute of Technology & Management, Bengaluru 24 – 28 July 2018	Fundamentals of nonlinear optics *(Invited)*
	Shahjalal University of Science and Technology, Bangladesh 5 August 2018	Research in ultrafast and nonlinear optics at the Raman Research Institute

Name	Conferences attended / Institutions visited	Title of paper/talk
	XLII Annual Meeting of the Optical Society of India – International Symposium on Optics 2018 Indian Institute of Kanpur, Kanpur 20 – 22 September 2018	Expansion dynamics of ultrafast laser produced metal plasmas *(Invited)*
	National Seminar on Functional Materials for Future Assumption College, Changanacherry 27 – 28 September 2018	Nonlinear optical behavior of core/shell nanomaterials with excellent optical limiting performance *(Invited)*
	Cochin University of Science and Technology, Kerala 21 October 2018	Physics Nobel Prize 2018
	Bangalore University, Bengaluru 22 November 2018	Chirped pulse amplification: Path to ultrafast, intense laser pulses
	National Seminar on Nascent and Sustainable Materials 2018 Kannur University, Kerala 28 – 30 November 2018	Nonlinear optical applications of novel materials *(Invited)*
	Colloquium Raman Research Institute, Bengaluru 29 November 2018	Physics Nobel 2018
	National Seminar on Nanomaterials: Synthesis and Characterization Al Ameen College, Alwaye 6 – 7 December 2018	Optical characterization of nanomaterials *(Invited)*
	National Conference on the Science and Applications of Functional Materials St. Joseph's College, Kerala 7 December 2018	Nonlinear optics of nanomaterials *(Invited, Keynote)*
	Indian Institute of Science, Bengaluru 12 December 2018	Physics Nobel Prize 2018
	International Conference on Complex and Functional Materials 2018 SN Bose National Centre for Basic Sciences Kolkata 13 – 16 December 2018	Optical limiting: Materials and methods *(Invited)*

Name	Conferences attended / Institutions visited	Title of paper/talk
	The 3rd International Conference on Optoelectronic and Nano Materials for Advanced Technology 2019 Cochin University of Science & Technology Cochin 2 – 5 January 2019	Optical power limiting with nanomaterials *(Invited)*
	KE College Mannanam, Kerala 5 January 2019	Optical power limiting with nanomaterials
	Workshop on the Physics of Materials Reva University, Bengaluru 24 – 25 January 2019	Nonlinear optical materials *(Invited)*
	National Conference on Nanomaterials 2019 LRG Govt. Arts College for Women Tirupur 24 – 25 January 2019	Optical power limiting by nanomaterials *(Invited)*
	The 5th International Conference on Nanoscience and Nanotechnology 2019 SRM University, Chennai 28 – 31 January 2019	Optical power limiting: Materials and methods *(Invited, keynote)*
	Indo-French Workshop on Physical and Mathematical Sciences Universite Cote d-Azur, France 4 – 8 February 2019	Light-matter interactions at moderate and high optical intensities: Nonlinear optics and laser-produced plasmas *(Invited)*
	Indian Academy Degree College Bengaluru 14 February 2019	Physics Nobel Prize 2018
Sadiq Rangwala	University of Connecticut, USA 1 – 3 April 2018	Refrigeration of ions with atoms
	Harvard University, USA 4 April 2018	
	Massachusetts Institute of Technology USA 4 – 5 April 2018	Refrigeration of ions with atoms
	Workshop on Few-body and Collective Many-body Behavior with Charge Impurities in Atomic Quantum Gases Hotel Eden Roc, Spain 18 – 20 July 2018	Ion-atom interactions in hybrid traps *(Invited)*

Name	Conferences attended / Institutions visited	Title of paper/talk
	26th International Conference on Atomic Physics Universitat de Barcelona, Spain 22 – 27 July 2018	Collisional cooling of trapped ions with ultracold atoms
	Workshop on Dynamics of Ultracold Systems with Embedded Highly-excited Rydberg Atoms Indian Institute of Science Education and Research, Bhopal 22 – 24 October 2018	Collisional cooling of trapped ions and its implications for ion transport *(Invited)*
	The 5th European Conference on Trapped Ions Weizmann Institute of Science, Israel 18 – 22 November 2018	Collisional cooling of trapped ions and its implications for ion transport *(Invited)*
	13th Asian International Seminar on Atomic and Molecular Physics Tata Institute of Fundamental Research Mumbai 3 – 8 December 2018	Trapped ion-atom interactions in cold and ultracold regimes *(Plenary)*
Saikat Das	IITB-ICTP Workshop on Neutrino Physics Indian Institute of Technology Bombay Mumbai 14 – 18 December 2018	
	International School on Astroparticle Physics Pierre Auger Observatory, Argentina 1– 9 March 2019	a.Ultrahigh energy cosmic rays and neutrinos from light nuclei composition b.Ultrahigh energy cosmic rays and cosmogenic neutrinos
Sandeep Kumar	Bannari Amman Institute of Technology Tamil Nadu 10 June 2018	Liquid crystals: The beautiful forth state of matter *(Invited)*
	Banaras Hindu University, Varanasi 12 July 2018	
	Vellore Institute of Technology, Vellore 18 August 2018	
	National Conference on Liquid Crystals and Nano Science Bannari Amman Institute of Technology Tamil Nadu 23 – 25 August 2018	Playing with discs *(Plenary)*

Name	Conferences attended / Institutions visited	Title of paper/talk
	National Conference on Advances in Chemical Sciences 2018 Manipal Institute of Technology Manipal 2 – 3 November 2018	Supramolecular nanocomposites as advanced materials for sustainability *(Keynote)*
	Andhra Pradesh Science Congress 2018 Yogi Vemana University, Kadapa 9 - 11 November 2018	Liquid crystalline nanocomposites as advanced materials for opto-electronics *(Invited)*
	Universite du Littoral Cote d'Opale, France 20 November 2018	Self-assembling supramolecular structures as advanced materials for opto-electronics *(Invited)*
	National Conference on Liquid Crystals Allahabad 19 – 21 December 2018	Hetero annulated triphenylene discotic liquid crystals *(Invited)*
	National Conference on Physics and Chemistry of Materials 2018 Devi Ahilya University, Indore 27 – 28 December 2018	Self-assembling supramolecular nanocomposites as advanced materials for opto-electronics *(Plenary)*
	Indian Institute of Technology, Guwahati 4 January 2019	
	4th Asian Conference on Liquid Crystals Ming Wah International Convention Center China 17 – 18 January 2019	Investigations on discotic liquid crystals *(Plenary)*
	North Bangalore University, Tamaka 28 February 2019	Liquid crystals: The intriguing fourth state of matter *(Invited)*
Sandhya	Keysight Education Symposium Agilent Technologies, Bengaluru 24 September 2018	RF/microwave and digital applications
Sanjay Kumar Behera	Annual European Rheology Conference The European Society of Rheology Italy 17 – 19 April 2018	
Sanjib Sabhapandit	Bangalore School on Statistical Physics – IX International Centre for Theoretical Sciences Bengaluru 27 June – 13 July 2018	*(Preparatory lectures)*

Name	Conferences attended / Institutions visited	Title of paper/talk
	Workshop on Probabilistic Methods in Statistical Physics for Extreme Statistics and Rare Events Centro De Giorgi, Italy 17 – 21 September 2018	Dynamics of stochastic resetting, with and without memory *(Invited)*
	Indian Statistical Physics Community Meeting International Centre for Theoretical Sciences Bengaluru 14 – 16 February 2019	Statistics of overtake events by a tagged agent
Saptarishi Chaudhuri	Conference on Dynamics of Ultracold Systems with Embedded Highly excited Rydberg Atoms Indian Institute of Science Education and Research, Bhopal 22 – 24 October 2018	Towards a sodium-potassium ultra-cold gas mixture experiment to explore many-body physics with long-range dipolar interactions
	International Conference on Quantum & Atom Optics 2018 Indian Institute of Technology, Patna 16 – 18 December 2018	Diffusion and fluctuations in ultra-cold atomic cloud
Sayantan Majumdar	Indian Institute of Science, Bengaluru 17 July 2018	Force induced adaptations in soft materials: from dense suspensions to biopolymers *(Invited)*
	2nd World Congress on Microscopy: Instrumentation, Techniques and Applications in Life Sciences and Materials Sciences Mahatma Gandhi University, Kottayam 10 – 12 August 2018	Force induced mechanical adaptations in soft condensed matter systems *(Invited)*
	Workshop on Entropy Information and Order in Soft Materials International Centre for Theoretical Sciences Bengaluru 28 – 31 August 2018	Memory retention in disordered bio-polymer networks
	India International Science Festival Indira Gandhi Pratishthan, Lucknow 5 – 8 October 2018	Force induced mechanical adaptations in soft condensed matter systems *(Invited)*
	Indian Institute of Technology, Tirupati 27 – 29 January 2019	Force induced jamming and yielding in dense particulate suspensions *(Invited)*

Name	Conferences attended / Institutions visited	Title of paper/talk
	Indian Statistical Physics Community Meeting International Centre for Theoretical Sciences Bengaluru 14 – 16 February 2019 Conference on Mechanics of Complex Matter: Criticality, Intermittency and Collective Behaviour Institute of Mathematical Sciences,Chennai 4 – 8 March 2019	Yielding in an athermal dense suspension Shear induced jamming and yielding in dense particulate suspensions *(Invited)*
Sebanti Chattopadhyay	Conference on Bioscopy Indian Institute of Science Education and Research, Kolkata 17 – 20 March 2019	Jamming and yielding in an athermal suspension of amorphous particles
Somashekar R	The Metre Wavelength Sky Conference - II National Centre for Radio Astrophysics Pune 18 – 22 March 2019	
Sridhar S	37th Meeting of Astronomical Society of India – SKA Workshop Christ University, Bengaluru 18 – 22 February 2019	Stalling of globular cluster orbits in dwarf galaxies *(Plenary, Invited)*
Srinivasa HT	Annual Conference/Workshop Karnataka Science and Technology Academy Christ University, Bengaluru 12 – 13 November 2018 International Conference on Advanced Materials, Energy & Environmental Sustainability 2018 University of Petroleum and Energy Studies Dehradun 14 – 15 December 2018 Indian Institute of Science, Bengaluru 14 March 2019	Shape anisotropic materials and their application in display devices Advanced materials, energy and environmental sustainability
Srivani KS	Xilinx Aerospace & Defence Summit 2018 Hotel Leela Palace, Bengaluru 11 December 2018	

Name	Conferences attended / Institutions visited	Title of paper/talk
	37th Meeting of Astronomical Society of India – SKA Workshop Christ University, Bengaluru 18 – 22 February 2019 The Metre Wavelength Sky Conference - II National Centre for Radio Astrophysics Pune 18 – 22 March 2019	Digital receiver architecture for low frequency aperture array of Square Kilometre Array
Sujatha S	Keysight Education Symposium Agilent Technologies, Bengaluru 24 September 2018	
Sumati Surya	University of Heidelberg, Germany 13 – 16 August 2018 Conference on Cosmology and Gravitational Physics with Lambda Nordic Institute for Theoretical Physics Sweden 30 July – 17 August 2018 Syracuse University, USA 1 – 2 October 2018 Quantum Gravity Seminar Perimeter Institute for Theoretical Physics Canada October – November 2018 WiM Fall Lecture Series Waterloo University, Canada 8 November 2018	Introduction to causal sets *(Invited)* The causal set path integral Defining spatial geometry via spacetime causal structure The causal structure of a physicist
Supurna Sinha	Math-Art Workshop Poorna Learning Centre, Bengaluru 8 April 2019 Kodaikanal Solar Observatory Kodaikanal 5 June 2018 Puri Polymer Conference Institute of Physics, Bhubaneswar 12 December 2018	a.Perspectives in Math and Art b.Fun with tiles DNA and magnetic fluxtubes Semiflexible polymer elasticity: The worm like chain model *(Invited)*

Name	Conferences attended / Institutions visited	Title of paper/talk
	Indian Statistical Physics Community Meeting International Centre for Theoretical Sciences Bengaluru 14 February 2019	Ring closure in semiflexible polymers
Urbasi Sinha	Quantum Frontiers and Fundamentals 2018 Raman Research Institute, Bengaluru 30 April – 4 May 2018	Quantum information related activities at RRI *(Organiser, Overview talk)*
	Frontiers of Science Meeting 2018 Royal Society, United Kingdom 15 – 18 May 2018	Quantum computing and key concepts that enable it *(Invited)*
	University of Cambridge, United Kingdom 21 May 2018	On superposition, interference and Feynman paths *(Invited)*
	International Conference on Photonics, Signal Processing and Communication Technologies M.S. Ramaiah University of Applied Sciences Bengaluru 18 – 20 July 2018	On superposition, interference and Feynman paths *(Invited, Expert)*
	National Workshop on Quantum Computing and Communication Technologies DRDO Bhawan, New Delhi 5 October 2018	Long distance quantum communication: Repeater and relay technologies and satellite based quantum key distribution *(Invited, Expert)*
	Institute for Quantum Science and Technology Seminar on Superposition Interference and Feynman Paths University of Calgary, Canada 21 November 2018	On superposition, interference and Feynman paths
	International Conference on Quantum Information Processing and Applications 2015 Harish-Chandra Research Institute Allahabad 2 – 8 December 2018	Two's company but three need not be a crowd *(Invited)*
	PSA Meeting on Quantum Computing Vigyan Bhavan, New Delhi 13 – 14 January 2019	Activities of the quantum information and computing lab *(Expert)*
	Colloquium on Superposition, Interference and Feynman Paths Saha Institute of Nuclear Physics, Kolkata 16 January 2019	

Name	Conferences attended / Institutions visited	Title of paper/talk
	Celebrating the Physics of Anthony Leggett: Tony Leggett's 80th Birthday Symposium Raman Research Institute, Bengaluru 3 – 4 February 2019	Two's company but three need not be a crowd *(Organiser, Overview talk)*
	Indo-French Workshop on Physical and Mathematical Sciences Universite Cote d-Azur, France 4 – 9 February 2019	Quantum information and computing lab *(Invited, Expert)*
	22nd National Conference on Atomic and Molecular Physics 2019 Indian Institute of Technology, Kanpur 25 – 28 March 2019	Manipulating light quanta *(Plenary)*
	Physics Colloquium Ashoka University, Haryana 27 March 2019	On Superposition and Feynman Paths
	Topical Meeting on Advances in Photonics 2019 National Institute of Science, Education and Research, Bhubaneswar 29 – 30 March 2019	Manipulating light quanta *(Invited)*
Urna Basu	Conference on Probabilistic Methods in Statistical Physics for Extreme Statistics and Rare Events Centro di Ricerca Matematica Ennio De Giorgi, Italy 17 – 21 September 2018	Active Brownanian Motion in Two Dimensions *(Invited)*
	International School for Advanced Studies Italy 23 – 26 September 2018	
	Institut fur Theoretische Physik, Germany 27 September – 2 October 2018	
	Saha Institute of Nuclear Physics, Kolkata 28 November – 2 December 2018	Frenetic aspects of nonlinear response: Theory and experiment
	Indian Statistical Physics Community Meeting International Centre for Theoretical Sciences Bengaluru 14 – 16 February 2019	Active Brownian motion in two-dimensions

Name	Conferences attended / Institutions visited	Title of paper/talk
Vani Hiremath	Librarians Day Celebration Sarada Ranganathan Endowment for Library Science PES University, Bengaluru 9 August 2018 Two day Workshop on Koha: An Integrated Library Management Software Indian Statistical Institute 21 – 22 March 2019	
Vijayaraghavan D	3rd International Conference on Nanomaterials, Synthesis, Characterization and Applications 2018 Mahatma Gandhi University, Kottayam 13 May 2018 3rd International Conference on Soft Materials 2018 Malaviya National Institute of Technology Jaipur 13 December 2018	Self-assembled ordering of single-walled carbon nanotubes in a lyotropic liquid crystal system *(Invited)* Effect of applied magnetic field on the phase transition temperature of a carbon nanotube-lyotropic liquid crystal composite
Vikram Rana	37th Meeting of Astronomical Society of India Christ University, Bengaluru 22 February 2019	Hard X-ray optics: A unique tool to probe the extreme universe
Vinutha C	37th Meeting of Astronomical Society of India – SKA Workshop Christ University, Bengaluru 18 February 2019	
Vivek M Vyas	Conference on Quantum Frontiers and Fundamentals: Experimental Studies and Theoretical Ramifications Raman Research Institute, Bengaluru 1 May 2018 Conference on Current Trends in QFT and Gravity SN Bose National Center for Basic Science Kolkata 5 December 2018	Coherence property of airy wavepackets Self accelerating quantum wave packets *(Invited)*

Colloquia and Seminars

Appendix - III

Name	Title	Date
Joydip Ghosh University of Wisconsin-Madison, USA	Fault-tolerant quantum computing with superconducting devices	02 April 2018
Partha Ghose The National Academy of Sciences Allahabad	Origin of quantum computers	03 April 2018
Tim Senden The Australian National University Australia	From nanomechanical work on molecular assemblies, to micro X-ray computed tomography for improved oil recovery	10 April 2018
Chennupati Jagadish The Australian National University Australia	Semiconductor nanowires for optoelectronics applications	10 April 2018
Sampurnanand Physical Research Laboratory, Ahmedabad	CMB Vs large scale structures: Tensions and remedies	16 April 2018
Prasanna Venkatesh Institute for Theoretical Physics, Austria	Cooperative effects in closely packed quantum emitters with collective dephasing	07 May 2018
Arpita Mitra Indian Institute of Technology, Kharagpur	Rational secret sharing: A quantum approach	07 May 2018
Mahavir Sharma University of Durham, UK	Cosmic reionization and its fozzils in the milky way	08 May 2018
Nimesh Patel Harvard-Smithsonian Center for Astrophysics USA	A new submillimeter wavelength radio telescope in the arctic region	14 May 2018
Fairoja Cheenicode Kabeer Uppsala University, Sweden	First-principle studies on the structural response of solids to ultrashort-laser and XUV pulses	05 June 2018
Narendra Nath Patra National Centre for Radio Astrophysics, Pune	The interstellar medium of dwarf galaxies	07 June 2018
Soumik Siddhanta Johns Hopkins University, USA	A plasmonics route towards spectroscopic fingerprinting of the tumor and its microenvironment	08 June 2018
Anjan Kumar Sarkar Indian Institute of Technology, Kharagpur	Prospects for measuring the HI 21-cm signal using the upcoming Ooty Wide Field Array (OWFA)	11 June 2018
Michael Berry University of Bristol, UK	Variations on a theme of Aharonov and Bohm	14 June 2018

Name	Title	Date
Bhabani Prasad Mandal Banaras Hindu University, Varanasi	Consistent quantum theories with Non-Hermitian systems	15 June 2018
Norman Murray Canadian Institute for Theoretical Astrophysics Canada	Star formation, GMCs and galaxies	18 June 2018
Balakrishnan Naduvalath University of Nevada, Las Vegas	Quantum engineered chemistry	25 June 2018
Nisha Rani University of Delhi, Delhi	Revisiting dark energy models using differential ages of galaxies	05 July 2018
Vivian Poulin Johns Hopkins University, USA	Shedding light on dark matter with cosmological observations	10 July 2018
Vasudev Shyam Perimeter Institute, Canada	Covariance and irrelevance in the holographic renormalization group	12 July 2018
Sambaran Banerjee Max Planck Institute, Germany	Star clusters: a versatile laboratory for astrophysical phenomena	16 July 2018
Eldad Bettelheim Hebrew University of Jerusalem, Israel	The Bethe Ansatz in and out of equilibrium	19 July 2018
Yaghoub Heydarzade Azarbaijan Shahid Madani University, Iran	Vaidya spacetime surrounded by cosmological fields (Webinar)	19 July 2018
P Praveen Bangalore University, Bengaluru	Optical tweezers as tools to probe colloids and membranes	23 July 2018
A Ravi P Rau Louisiana State University, USA	Fifteen schoolgirls spread (5X3) across a week, a pair of qubits and a rainbow of four basic colours: Common patterns	25 July 2018
Sahil Saini Louisiana State University, USA	Quantization ambiguities and singularity avoidance in loop quantum cosmology	26 July 2018
Abhishek Majhi National Autonomous University of Mexico Mexico	Aspects of black hole entropy from quantum geometry revisited	30 July 2018
Saubhik Sarkar Harish-Chandra Research Institute, Allahabad	Impurity entanglement with Bosons in optical lattices	03 August 2018
Jayaram N Chengalur National Centre for Radio Astrophysics, Pune	Angular momentum of dwarf galaxies	06 August 2018
Bibhu Ranjan Sarangi SRM Research Institute, Chennai	Force mapping at focal adhesions	08 August 2018

Name	Title	Date
M Muthukumar University of Massachusetts, USA	Movements of charged macromolecules in crowds	13 August 2018
Tanay Roy Tata Institute of Fundamental Research Mumbai	Multi-mode superconducting circuits for building programmable multi-qubit quantum processors	13 August 2018
Arjun Mani National Institute of Science Education and Research, Bhubaneswar	Studies on edge mode transport in quantum Hall, quantum spin Hall and quantum anomalous Hall samples	14 August 2018
D Madhumitha Central Leather Research Institute, Chennai	Rheological studies of protein colloidal clusters at interfaces	16 August 2018
Saroj Kumar Nandi Weizmann Institute of Science, Israel	Effects of activity on the glassy properties of an active system	20 August 2018
Deepak Kumar University of Massachusetts, USA	Elastocapillary phenomena with thin films	20 August 2018
Ramprasad Rao ASIAA/Sub Millimeter Array, Hawaii	Science with the upgraded SMA in the next decade	24 August 2018
Prabhat Tripathi University of Massachusetts, USA	When two polymers meet in a nanopore	28 August 2018
Niranjan Myneni Raman Research Institute, Bengaluru	Theory of diffusion of an ion in an ultra-cold atomic cloud	29 August 2018
Shriharsh Tendulkar University of McGill, Canada	CHIME and FRBs	30 August 2018
Nisant Kumar Singh Max Planck Institute for Solar System Research, Germany	Bihelical solar magnetic fields, active regions and its interaction with the surface gravity mode	10 September 2018
KS Vasu University of Manchester, UK	Molecules at confined interfaces and capillaries	11 September 2018
A Gopakumar Tata Institute of Fundamental Research Mumbai	Blazar OJ287 and its nano-Hertz GW emitting massive BH binary central engine	12 September 2018
Raj Kumar Khan University of Calcutta, Kolkata	Self-assembling properties of short bent-core molecules: Exhibition of rich variety of mesophases	24 September 2018
Mahesh Bandi Okinawa Institute of Science & Technology Japan	A superficial relationship: Soap spreading in water	24 September 2018

Name	Title	Date
Susan Coppersmith University of Wisconsin-Madison, USA	Building a quantum computer using silicon quantum dots	27 September 2018
Mayukh Lahiri University of Vienna and Institute for Quantum Optics & Quantum Information Austria	Quantum imaging and two-photon correlation measurement with undetected photons	01 October 2018
Stephan Herminghaus Max Planck Institute for Dynamics and Self Organisation, Germany	Artificial microswimmers: Individual and collective phenomena	05 October 2018
Arnab Pal Tel Aviv University, Israel	First passage under restart	10 October 2018
Basudeb Dasgupta Tata Institute of Fundamental Research Mumbai	Flavor dynamics of neutrinos from core-collapse supernovae	30 October 2018
Chitra Shaji Pondicherry University, Puducherry	Stokes-Mueller polarimetric studies in linear and nonlinear optical processes	14 November 2018
Amol S Dighe Tata Institute of Fundamental Research Mumbai	Astroparticle physics of neutrinos	15 November 2018
Reji Philip Raman Research Institute, Bengaluru	Physics Nobel 2018	29 November 2018
Ulrich Eismann TOPTICA Photonics AG, Germany	Advanced lasers for quantum technologies - and beyond	30 November 2018
Bulbul Chakraborty Brandeis University, USA	Shear induced rigidity in granular materials - a statistical approach	30 November 2018
Satyendra Thoudam Linnaeus University, Sweden	Cosmic-ray origin and propagation: Implication from new measurements and future perspectives	30 November 2018
Chandreyee Maitra Max Planck Institute for Extraterrestrial Physics, Germany	Neutron stars as central engines of ultra-luminous X-ray sources	03 December 2018
Deepak Pandey University Bonn, Germany	From macroscopic to microscopic optical resonators: A quantum technology perspective	04 December 2018
Tridib Ray Graduate University, Japan	Evanescent field interaction of light with cold atoms	11 December 2018
Jasleen Lugani University of Oxford, UK	Integrated photonics for quantum optics experiments	17 December 2018

Name	Title	Date
Sivasurender Chandran University of Freiburg, Germany	Time matters: Predicting the nonequilibrium behavior of polymers	18 December 2018
Renu Maan Delft University of Technology, Netherlands	Towards making a minimal synthetic cell	20 December 2018
Subir Sarkar University of Oxford, UK	Cosmic ray acceleration in the laboratory	27 December 2018
Vikas Gupta University of Delhi and All India Forum for Right to Education, Delhi	A critical look at the New Education Policy: Interaction with scientists	08 January 2019
Shreyas Kaptan Freie Universitat Berlin, Germany	Regulation of permeation in aquaporins	08 January 2019
R Rajesh Institute of Mathematical Sciences Chennai	Velocity distribution of driven granular gases	13 January 2019
Marc Geiller Laboratoire de Physique Theorique et Modeles Statistique, France	Quantum space-time and topological phases	14 January 2019
Ramesh Bhat Curtin University, Australia	Geodetic precession in the binary PSR J1141-6545	16 January 2019
Tanvi Karwal Johns Hopkins University, USA	Early dark energy and the Hubble tension	17 January 2019
Raghuram Murtugudde The University of Maryland, USA	El, Nino dynamics, flavors, predictions: Why are some predictions failing?	17 January 2019
Niladri Paul Inter-University Centre for Astronomy & Astrophysics, Pune	Halo model of galaxies and gas	21 January 2019
Kali Prasanna Nayak University of Electro-Communications, Japan	Developing a quantum interface on a tapered optical fiber	21 January 2019
Rohan Singh Los Alamos National Laboratory, USA	Ultrafast spectroscopy of semiconductor nanostrcutures	22 January 2019
Gunjan Verma Indian Institute of Science Education and Research, Pune	Dynamics of Bose-Einstein Condensate: Linear and non-linear regime	29 January 2019
Vikram Soni Jamia Millia Islamia and Jawaharlal Nehru University, Delhi	Mysterious magnetars: Maximum stars	05 February 2019

Name	Title	Date
Thomas B Bahder Army Research Office, Tokyo	Topological quantum sensors	07 February 2019
Debdutta Paul Tata Institute of Fundamental Research Mumbai	Using gamma ray bursts to detect high-energy cosmic rays in AstroSat-CZT imager	12 February 2019
Satya Majumdar Laboratoire de Physique Theorique et Modeles Statistique, France	Active Brownian motion in two dimensions	12 February 2019
R Rajesh Institute of Mathematical Sciences, Chennai	Velocity distribution of driven granular gases	13 February 2019
Sreeram K Kalpathy Indian Institute of Technology, Madras Chennai	Patterning liquid flow by thermal and wettability gradients	15 February 2019
Ganesh Bagler International Institute of Information Technology, Delhi	The science of computational gastronomy	21 February 2019
Aarti Joshi Aryabhatta Research Institute of Observational Sciences, Nainital	Multi-wavelength study of magnetic cataclysmic variables	05 March 2019
Uma Ramakrishnan National Centre for Biological Sciences Bengaluru	Tigers on island	07 March 2019
N Mukunda Indian Academy of Sciences, Bengaluru	V-A' and Diagonal Representation': ECG Sudarshan's work on the weak interactions and in quantum optics	19 March 2019
G Baskaran Institute of Mathematical Sciences Chennai	Voyage in Hilbert space	21 March 2019
Abhishek Dhar International Centre for Theoretical Sciences Bengaluru	Patterns in randomness	29 March 2019

International Conference on Quantum Frontiers and Fundamentals

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Contributed Talks

Name & Institute/University	Title of the Talk
Suman Chand Indian Institute of Technology, Ropar	Quantum heat machines with trapped ions
Jebarathinam Chellasamy S. N. Bose National Centre for Basic Sciences, Kolkata	Simultaneous correlations in complementary bases as quantitative resource for quantum steering
Debmalya Das Harish-Chandra Research Institute, Allahabad	Quantum heat engine using stirling cycle and resources of ignorance
Siddhant Das Ludwig Maximilian University of Munich, Germany	Arrival time distributions of spin-1/2 particles
Nicolo Lo Piparo National Institute of Informatics, Tokyo	Single photon entanglement distribution scheme applied to a purification protocol
Shiladitya Mal Harish-Chandra Research Institute, Allahabad	Temporal correlations and device-independent randomness
Atul Mantri Singapore University of Technology & Design and Centre for Quantum Technologies, Singapore	Flow ambiguity: a path towards classically driven blind quantum computation
Chiranjib Mukhopadhyay Harish-Chandra Research Institute, Allahabad	Fifty shades stronger: variance based sum uncertainty and reverse uncertainty relations for arbitrary quantum states and all incompatible observables
Tanumoy Pramanik Korea Institute of Science and Technology, South Korea	Experimental verification of hidden steerability
Tabish Qureshi Jamia Millia Islamia, New Delhi	Two-slit interference of entangled photons
Prabhu R Indian Institute of Technology Dharwad, Dharwad	Dynamics and steady state properties of entanglement in periodically driven ising spin-chain
Aravinda S Institute of Mathematical Sciences, Chennai	Geometric construction of ontological models for single systems in the convex framework
Debashis Saha University of Gdansk, Poland	Preparation contextuality as the fundamental resource in quantum communication
Saubhik Sarkar Harish-Chandra Research Institute, Allahabad	Disorder and noise induced dynamics in fermi-hubbard

Name & Institute/University	Title of the Talk
Sk Sazim Harish-Chandra Research Institute, Allahabad	Coherence makes quantum systems magical
Arun Sehrawat Harish-Chandra Research Institute, Allahabad	Quantum constraints stronger than uncertainty relations
Kumar Shivam Raman Research Institute, Bengaluru	Lorentzian Geometry for detecting qubit entanglement
George Thomas Institute of Mathematical Sciences, Chennai	Coupled systems as thermodynamic machines: efficiency, work and quantum correlations
Marco Toros University of Southampton, UK	Detection, and control of optically levitated particles
Vivek Vyas Raman Research Institute, Bengaluru	Coherence property of airy wavepackets

Posters

Name	Title of the Poster
Nasir Alam Jaypee Institute of Information Technology, Noida	Higher order nonclassicality: where can we find it?
Bikash Behera Indian Institute of Science Education and Research, Kolkata	Experimental demonstration of quantum tunneling
Subhajit Bhar Raman Research Institute, Bengaluru	Experimental certification and quantification of entanglement in a novel spatially correlated bipartite qutrit system
Rajendra Singh Bhati Indian Institute of Science Education and Research, Mohali	Analyzing nested mach-zehnder interferometer with weak path marking on internal degrees of freedom
Debarshi Das Bose Institute, Kolkata	Steering a single system sequentially by multiple observers
Chandan Datta Institute of Physics, Bhubaneswar	An authentication protocol based on polygamous
Rengaraj G Raman Research Institute, Bengaluru	Measuring the deviation from the superposition principle in interference experiments
Akshay Gaikwad Indian Institute of Science Education and Research Mohali	Experimental demonstration of selective quantum process tomography on an nmr quantum information processor

Name & Institute/University	Title of the Poster
Shamiya Javed University of Allahabad, Uttar Pradesh	Improvement of probabilistic quantum teleportation
Kaushik Joarder Raman Research Institute, Bengaluru	Loophole free test of macro-realism in optical system
Anjali K Bangalore University, Bengaluru	Nonlocality and entanglement in symmetric multiqubit states
Aiman Khan Indian Institute of Technology, Roorkee	Identifying and quantifying resource for remote
Asmita Kumari National Institute of Technology, Patna	Swapping intra-photon entanglement to inter-photon entanglment using linear optical devices
Alvaro Mozota Frauca Perimeter Institute, Canada	How to measure the quantum measure
Ravi Kamal Pandey University of Allahabad, Allahabad	Controlled entanglement diversion using ghz type entangled coherent state
Devashish Pandey Universitat Autonoma de Barcelona, Spain	Non-universality of quantum dynamics computed from time-correlation functions
Muthuganesan R National Institute of Technology, Tiruchirapalli	Robustness of measurement induced nonlocality to sudden death
Syed Raunaq Ahmed Bangalore University, Bengaluru	Noise tolerance of N-qubit symmetric states in discriminating rotations
Anirudh Reddy Raman Research Institute, Bengaluru	Effect of thermal noise on optimal cloning of quantum states
Saptarshi Roy Harish-Chandra Research Institute, Allahabad	Deterministic quantum dense coding networks
Surya Sahoo Raman Research Institute, Bengaluru	Inferring expectation value of non-hermitian operator from visibility
Souradeep Sasmal Bose Institute, Kolkata	Exploring linear steering inequalities from state space structure
Mushtaq Shah National Institute of Technology, Jammu & Kashmir	Non-classicality with q-calculus
Gautam Sharma Harish-Chandra Research Institute, Allahabad	Quantum uncertainty relation based on the mean deviation
B Sharmila Indian Institute of Technology, Madras	Entangled quantum states: nonclassical effects and entanglement indicators

Name & Institute/University	Title of the Poster
Mohd Asad Siddiqui Indian Institute of Science Education and Research, Mohali	Tight upper bound for the maximal quantum value of the mermin operators
Amandeep Singh Indian Institute of Science Education and Research, Mohali	Experimental entanglement detection of unknown tripartite states on spin ensemble using nmr
Ashutosh Singh Raman Research Institute, Bengaluru	Manipulation of entanglement sudden death in an all-optical experimental setup
Mitali Sisodia Jaypee Institute of Information Technology, Noida	Our experience with the IBM quantum experience
Shrikant Utagi Poornaprajna Institute of Scientific Research, Bengaluru	Quantum key distribution in a noise-restricted-adversary model
Seeta Vasudevrao Bangalore University, Bengaluru	The Margenau-Hill quasi-probabilities for symmetric two qubit system and joint measurability

International Symposium - Celebrating Sir Anthony Leggett's 80th Birth Anniversary!

3 - 4 February 2019 | Venue: Raman Research Institute, Bengaluru

Name	Title
03-Feb-19	
Anthony Leggett	A 60-year career in physics: Recollections and reflections
T V Ramakrishnan	Leggett, superconductivity and superfluidity
Jainendra Jain	Beyond composite fermions
G Baskaran	Two fluid model of Mott transition
Rafael D Sorkin	"Persistence of zero" as an intrinsic causality criterion
SM Roy	Contractive states and non-locality
Arindam Ghosh	Leveraging charge-transfer across atomic layers
H R Krishnamurthy	Surprises in the t-J model, and implications for superconductivity in Cuprates
Chandan Das Gupta	Supersolid behaviour from superfluidity along extended defects
A.K. Raychaudhari	Quantum mechanical tunnelling states in glasses
Pratap Raychaudhuri	Observation of hexatic vortex fluid in a thin superconducting film
Leong Chuan Kwek	Atomtronics: Towards sensors and devices with ultracold atoms and optical lattices
04-Feb-19	
Spenta Wadia	The Sachdev-Ye-Kitaev (SYK) toy model of black hole Physics in 2-dims.
Sougato Bose	Nonclassicality with Mesoscopic Levitated Objects
Diptiman Sen	Josephson junctions of multiple superconducting wires
Kalobaran Maiti	Superconductivity in 122 class of Fe-pnictides
Pushan Ayyub	Superconductivity in finite solids
Arghya Taraphder	Emergence at the oxide interface
Arun K Pati	Measurring Non-Hermitian value with weak value
ND Hari Dass	Can weak measurements restore the sanctity of the individual in quantum mechanics?
M Pawlowski	Leggett-Garg inequalities in device independent cryptography
Shobhana Narasimhan	The clearness of the Object- Elements of style in scientific writing
Dipankar Home	For whom the bell tolls: Nonlocality and randomness
Urbasi Sinha	Two's company but three need not be a crowd
Discussion Session	Physics in the 21st Century: Open questions and future directions

Visitors

Appendix - IV

Sl. No	Name and Institution	Duration of Stay
1	Joydip Ghosh University of Wisconsin-Madison, USA	1 - 3 April 2018
2	Sampurnand Physical Research Laboratory, Ahmedabad	1 - 27 April 2018
3	K Asha Kuvempu University, Shimoga	1 April 2018 - 20 January 2019 7 - 13 March 2019
4	Partha Ghose The National Academy of Sciences, Allahabad	2 - 5 April 2018
5	Tim Senden The Australian National University, Australia	10 April 2018
6	Dheeraj K Dedhia Tata Institue of Fundamental Research, Mumbai	27 - 28 April 2018
7	Prasanna Venkatesh Institute for Quantum Optics and Quantum Information and Institute for Theoretical Physics, Innsbruck	6 - 8 May 2018
8	Mahavir Sharma University of Durham, UK	6 - 9 May 2018
9	Arpita Maitra Indian Institute of Technology, Kharagpur	6 - 12 May 2018
10	Kishore Pulapalli Indian Institute of Astrophysics, Bengaluru	7 - 14 May 2018
11	Garima Rani Institute of Mathematical Sciences, Chennai	8 - 11 May 2018
12	Nimesh Patel Harvard-Smithsonian Center for Astrophysics, USA	14 - 16 May 2018
13	Subhash Karbelkar Birla Institute of Technology & Science, Hyderabad	15 - 16 May 2018
14	Mohammad Shafi Ollakan PSMO College, Tirurangadi	17 - 24 May 2018
15	Vanessa Rodrigues Manipal University, Manipal	21 May - 21 June 2018 14 August - 4 September 2018
16	Yuri Shchekinov Lebedev Physical Institute, Russia	22 May - 23 June 2018

Sl. No	Name and Institution	Duration of Stay
17	Frincy Fransis St. Theresa's College, Ernakulam	25 - 27 May 2018
18	KK Anoop Cochin University of Science & Technology, Cochin	30 May - 13 June 2018 25 - 27 November 2018
19	Hanna Mariya St. Theresa's College, Ernakulam	25 - 31 May 2018
20	B Indumati Lady Doak College, Madurai	1 - 15 June 2018
21	K Janani Archana Lady Doak College, Madurai	1 - 15 June 2018
22	Anju Muralidharan Cochin University of Science & Technology, Cochin	1 - 15 June 2018
23	Narendra Nath Patra National Centre for Radio Astrophysics, Pune	3 - 8 June 2018
24	Ayyappan Jayaraman Government College of Engineering, Thanjavur	4 - 11 June 2018 15 - 16 December 2018
25	Fairoja Cheenicode Kabeer Uppsala University, Sweden	05 June 2018
26	Gaurav Tomar Indian Institute of Science, Bengaluru	08 June 2018
27	Anjan Kumar Sarkar Indian Institute of Technology, Kharagpur	9 - 11 June 2018
28	Smita Mathur Ohio State University, USA	17 - 19 June 2018
29	Balakrishnan Naduvalath University of Nevada, USA	24 - 26 June 2018
30	Nisha Rani University of Delhi, Delhi	1 - 15 July2018
31	Rajeev Misra Inter-University Centre for Astronomy & Astrophysics, Pune	4 - 5 July 2018
32	Gulab Chand Dewangan Inter-University Centre for Astronomy & Astrophysics, Pune	4 - 5 July 2018
33	Rishi Khatri Tata Institue of Fundamental Research, Mumbai	4 - 7 July 2018

Sl. No	Name and Institution	Duration of Stay
34	Tuhin Ghosh National Institute of Science Education and Research, Odisha	4 - 7 July 2018
35	Tarun Souradeep Ghosh Inter-University Centre for Astronomy & Astrophysics, Pune	4 - 7 July 2018
36	Jaques Delabrouille Laboratoire Astroparticule and Cosmologie, Paris	4 - 7 July 2018
37	Lakshmanan Sriramkumar Indian Institute of Technology-Madras, Chennai	4 - 7 July 2018
38	Vivian Poulin Johns Hopkins University, USA	6 - 20 July 2018
39	Kishore Sridharan Mangalore University, Mangalore	9 - 14 July 2018
40	Fabrien Bretenaker CNRS Laboratoire Aime Cotton, France	11 - 28 July 2018 16 - 19 December 2018
41	Vasudev Shyam Perimeter Institute, Canada	12 July 2018
42	Sambaran Banerjee Max Planck Institute, Germany	15 - 19 July 2018
43	Ravi P Rau Louisiana State University, USA	15 - 29 July 2018
44	Yaghoub Heydarzade Azarbaijan Shahid Madani Univeristy, Iran	19 July 2018
45	Rama Govindarajan International Centre for Theoretical Sciences, Bengaluru	20 July 2018
46	T.R. Sheshadri University of Delhi, Delhi	23 July 2018
47	P Praveen Bangalore University, Bengaluru	23 July 2018
48	Sahil Saini Louisiana State University, USA	26 July 2018
49	Ritaban Chatterjee Presidency University, Kolkata	27 - 29 July 2018
50	Abhishek Majhi National Autonomous University of Mexico, USA	30 July 2018

Sl. No	Name and Institution	Duration of Stay
51	Saubhik Sarkar Harish-Chandra Research Institute, Allahabad	23 July - 4 August 2018
52	Yashwant Gupta National Centre for Radio Astrophysics, Pune	1 - 2 August 2018
53	M Muthukumar University of Massachusetts, USA	5 - 24 August 2018
54	Bibhu Ranjan Sarangi SRM Research Institute, Chennai	6 - 10 August 2018
55	Shilpi Chakraborty Indian Institute of Technology, Indore	6 - 18 August 2018 8 December 2018 - 1 January 2019 10 - 30 March 2019
56	Jijil JJ Nivas University of Naples Federico, Italy	11 - 14 August 2018
57	Tanay Roy Tata Institute of Fundamental Research, Mumbai	12 - 13 August 2018
58	Arjun Mani National Institute of Science Education and Research Bhubaneswar	12 - 18 August 2018
59	D Madhumitha Central Leather Research Institute, Chennai	16 August 2018
60	Deepak Kumar University of Massachusetts, USA	18 - 21 August2018
61	Saroj Kumar Nandi Weizmann Institute of Science, Israel	20 August 2018
62	Ramprasad Rao ASIAA/Sub Millimeter Array, Hawaii	24 August 2018
63	Sandeep Choudari Giant Metrewave Radio Telescope, Pune	27 - 29 August 2018
64	Harshvardhan Reddy Giant Metrewave Radio Telescope, Pune	27 -29 August 2018
65	Parag B Shaw Tata Institute of Fundamental Research, Mumbai	27 - 29 August 2018
66	Bhaswati Mookerjee Tata Institute of Fundamental Research, Mumbai	27 - 29 August 2018
67	Kaushal Buch Giant Metrewave Radio Telescope, Pune	27 - 29 August 2018

Sl. No	Name and Institution	Duration of Stay
68	Prabhat Tripathi University of Massachusetts, USA	28 August 2018
69	Shriharsh Tendulkar University of McGill, Canada	29 - 31 August 2018
70	Amitabha Chattopadhyay Centre for Cellular and Molecular Biology, Hyderabad	07 September 2018
71	Smijesh Nadarajan Achary Umea University, Sweden	9 -11 September 2018
72	KS Vasu University of Manchester, UK	9 - 12 September 2018
73	A Gopakumar Tata Institute of Fundamental Research, Mumbai	9 - 16 September 2018
74	Nisant Kumar Singh Max-Planck Institute for Solar Systems Research, Germany	9 - 16 September 2018
75	Raj Kumar Khan University of Calcutta, Kolkata	23 - 27 September 2018
76	Mahesh Bandi Okinawa Institute of Science and Technology, Japan	28 September 2018
77	Olivier Dulieu Laboratoire Aime Cotton, France	25 September - 4 October 2018
78	Mayukh Lahiri University of Vienna and Institute of Quantum Optics & Quantum Information, Vienna	29 September - 5 October 2018
79	Stephan Herminghaus Max-Planck Institute for Dynamics and Self-organization Germany	05 October 2018
80	Arnab Pal Tel Aviv University, Israel	6 - 12 October 2018
81	Dipankar Home Bose Institute, Kolkata	9 - 14 October 2018 28 January - 6 February 2019
82	Chitra Shaji Pondicherry University, Puducherry	13 - 14 November 2018
83	Amol S Dhige Tata Institute of Fundamental Research, Mumbai	15 - 16 November 2018
84	Manish Kumar University of Aveiro, Portugal	20 November - 2 December 2018

Sl. No	Name and Institution	Duration of Stay
85	Ulrich Eismann TOPTICA Photonics AG, Germany	29 November - 3 December 2018
86	Bulbul Chakraborty Brandeis University, USA	30 November 2018
87	Deepak Pandey University Bonn, Germany	1 - 5 December 2018
88	Tridib Ray Graduate University, Japan	10 - 13 December 2018
89	Jasleen Lugani University of Oxford, UK	16 - 17 December 2018
90	Sivasurender Chandran University of Freiburg, Germany	18 December 2018
91	Renu Maan Delft University of Technology, Netherlands	20 December 2018
92	Kaisia Rejner University of York, UK	30 December 2018 - 14 January 2019
93	Rafael Sorkin Perimeter Institute of Theoretical Physics, Canada	1 January - 5 February 2019
94	Stav Zalel Imperial College, London	7 January - 19 March 2019
95	Shreyas Kaptan Freie Universitat Berlin, Germany	08 January 2019
96	Vikas Gupta University of Delhi, Delhi	08 January 2019
97	Miguel Campiglia University of Republic, Uruguay	10 - 17 January 2019
98	Marc Geiler Laboratoire De Physique Theorique Et Modeles Statistique France	10 - 20 January 2019
99	Ramesh Bhat Curtin University, Australia	14 - 25 January 2019
100	Satya Majumdar Laboratoire De Physique Theorique Et Modeles Statistique France	15 January - 15 February 2019
101	Raghuram Murtugudde University of Maryland, USA	16 - 19 January 2019

Sl. No	Name and Institution	Duration of Stay
102	Niladri Paul Inter-University Centre for Astronomy & Astrophysics, Pune	20 - 21 January 2019
103	Kali Prasanna Nayak University of Electro-Communications, Japan	20 - 23 January 2019
104	Priyanka Singh National Institute for Astrophysics, Italy	20 - 25 January 2019
105	Shahnawaz Malik University of Kashmir, Srinagar	20 January - 19 February 2019
106	Rohan Singh Los Alamos National Laboratory, USA	21 - 24 January 2019
107	Dhiraj K Dedhia Tata Institute of Fundamental Research, Mumbai	21 - 26 January 2019
108	Igor Musevic University of Ljubljana, Slovenia	22 - 25 January 2019
109	Jebarathinam SN Bose National Centre for Basic Sciences, Kolkata	23 - 25 January 2019
110	Vikram Soni Jamia Millia Islamia and Jawaharlal Nehru University, Delhi	3 - 7 February 2019
111	Atharva Kulkarni Savitribai Phule Pune University, Pune	6 - 22 February 2019
112	Thomas B Bahder Army Research Office, Japan	07 February 2019
113	Arun Kumar Pati Harish-Chandra Research Institute, Allahabad	9 - 25 February 2019
114	Sandeep Kumar Yadav Guru Jambheshwar University of Science & Technology Haryana	11 - 13 February 2019
115	Debdutta Paul Tata Institute of Fundamental Research, Mumbai	11 - 17 February 2019
116	R Rajesh Institute of Mathematical Sciences, Chennai	12 - 13 February 2019
117	Sreeram K Kalpathy Indian Institute of Technology-Madras, Chennai	15 February 2019
118	Arti Joshi Aryabhatta Research Institute of Observational Sciences, Nainital	28 February - 8 March 2019

Sl. No	Name and Institution	Duration of Stay
119	Hrishikesh Shetgaonkar Birla Institute of Technology & Science, Pilani	20 - 31 March 2019
120	G Baskaran Institute of Mathematical Sciences, Chennai	21 - 22 March 2019
121	Madhuri Katti Mahadevi Birla World Academy, Kolkata	28 - 31 March 2019
122	Abhishek Dhar International Centre for Theoretical Sciences, Bengaluru	29 March 2019

RRI Science Forum

Appendix - V

Sl. No	Discussed by	Paper Discussed	Date
1	Urbasi Sinha & Ashutosh Singh	Experimental two-way communication with one photon	26 April 2018
2	Raghunathan A	Detection of high energy particles using higher wavelengths	10 May 2018
3	Joseph Samuel	Pitch Perfect: Pythagoras and the well tempered scale	28 June 2018
4	Andal Narayanan & Pradosh Kumar Nayak	Non-demolition measurement of microwaves at the single-photon level	26 July 2018
5	Nayantara Gupta & Saikat Das	Astrophysical neutrinos, ultrahigh energy cosmic rays and cosmogenic neutrinos	09 August 2018
6	Prabu T	Pulsar timing array experiments: Basics and current updates	23 August 2018
7	Supurna Sinha	Perspectives in math and art	25 October 2018
8	Ranjini Bandyopadhyay	A fluid-to-solid jamming transition underlies vertebrate body axis elongation	22 November 2018
9	Sayantan Majumdar	Static-friction between solid surfaces: It's not very static	13 December 2018
10	Narendranath Patra	The missing satellite problem and the dark galaxies	24 January 2019
11	Kshitija Kelkar	First galaxies through the Hubble frontier fields	14 March 2019
12	Ayush Agrawal & Sreeja Sasidharan	Origin of hydrophobicity and enhanced water hydrogen bond strength near purely hydrophobic solutes	28 March 2019

Visiting Students' Programme

Appendix - VI

Mentor	Students		
Andal Narayanan	Arpit Behera Kaarthik Varma Mohammed Zia		
Biman Nath	Pushpita Das		
Biswajit Paul	Ketan Rikame		
Deshpande AA	Akhil Jaini Satyapan Munshi Harsh Grover Yash Bhusare Saloni Priya	Boris Sindhu Kalita Simran Gupta Pavan U A Amar Suryavanshi Nishi Tiwari	Mohini Ramwala Aleena Baby Shalini Singh Hrishikesh Shetgaonkar
Dibyendu Roy	Srikant Ganguly Vishwajith E S		
Gautam Soni	Aakanksha Agarwal Priyanka Arunachalam Satish Kumar Mehta	Surabhya Balasubramanian Tinku Naik Banavathi	
Hema Ramachandran	Akhil V K Vasuki M Sayan Ghosh Harsha S	Arvind Ganesh Anju Mauraleedharan Vishnupriya P V Shashank Kumar	Satvika Bandaruppay Chandrika Avvaru Anubodh Yadav
Jacob Rajan	Arjun M Pavan Kumar A		
Joseph Samuel	Aswaty Vijay Shivan Khullar		
T Prabu	Abhishek R Arul Pandian B Ganesh L	Jyothsna Jois Rachna M Sathish R	
Pramod Pullarkat	Ajmal S Madhusudhan P	Shrinivas Jayaram Sabahat Shaikh	
R Pratibha	Avani Tiwari Lahari B L Rai Navya G R		
A Raghunathan	Akash V Kulkarni		
VA Raghunathan	Vineetha		
B Ramesh	Geethu Paulose Kamesh S Kuldeep Singh	Pinaki Roy Rishikesh Dudhat	

Mentor	Students		
Ranjini Bandyopadhyay	Tonmoy Gogoi		
Ravi Subrahmanyan	Samskruti Ganjam		
Reji Philip	Arjun K K Ashly Jose Beryl C	Joel K Jose Kiran Michael Priya Dominic	
Sandeep Kumar	Anu Vashishtha Deepika Hari Shanker K	Shikha Singh Shrikrishna Dutta Verma Swasthika	Tripti Agnihotri Viditha
Saptarishi Chaudhuri	Anindya Sundar Paul G L Priyanka	Yateendra Sihag Rohit Prasad Bhatt	
Sayantan Majumdar	Firoz M K Neil Ashwin Raj Vaisakh V	Raju Sarkar Subhransu Dhar	Vidhu Catherine Antony Nivya Theresa Jose
KS Srivani	Rachel Babu		
Sumati Surya	Shikhar Mittal		
Urna Basu	Christy Pius		
D Vijayaraghavan	Jai Mishra Thejas R		
Vikram Rana	Koyena Das		

RAMAN RESEARCH INSTITUTE

Audited Statement of Accounts
2018-2019

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 2019, 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, the accompanying financial statements give a true and fair view of the financial position of the Institute as at March 31, 2019, and of its financial performance and its cash flows 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 entity 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 cash flows of the entity 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.

e-mail : services@grsmca.com *Website : www.grsmca.com*

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.

For GRSM & ASSOCIATES
Chartered Accountants
FRN: 000863S

GOPALKRISHNA HEGDE
M.No.208063
Partner

Place: Bangalore
Date: 4th July 2019
UDIN : 19208063AAAABX2032

RAMAN RESEARCH INSTITUTE, BENGALURU
BALANCE SHEET AS AT 31ST MARCH 2019

(Amount in INR)

CORPUS/CAPITAL FUND AND LIABILITIES	Schedule	Current Year	Previous Year
Corpus/Capital Fund	1	105,60,91,329	106,78,29,204
Reserves & Surplus	2	-	-
Earmarked & Endowment Funds	3	67,09,33,875	59,49,76,437
Secured Loans & Borrowings	4	-	-
Unsecured Loans & Borrowings	5	-	-
Deferred Credit Liabilities	6	-	-
Current Liabilities & Provisions	7	2,33,87,719	1,89,01,532
TOTAL		**175,04,12,923**	**168,17,07,173**
ASSETS			
Fixed Assets	8	92,31,35,873	92,10,51,006
Investments- from earmarked & endowment funds	9	65,99,47,147	57,69,98,344
Investments-Others	10	1,00,00,000	1,00,00,000
Current Assets, Loans & Advances	11	15,73,29,903	17,36,57,823
TOTAL		**175,04,12,923**	**168,17,07,173**
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/-
(C. S. R. Murthy)
Administrative Officer

Sd/-
(Ravi Subrahmanyan)
Director

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

BENGALURU / 4th July 2019

RAMAN RESEARCH INSTITUTE, BENGALURU

INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR ENDED 31ST MARCH 2019

(Amount in INR)

INCOME	Schedule	Current Year	Previous Year
Income from Sales/Services	12	-	-
Grants/Subsidies	13	50,87,81,568	44,98,23,193
Fee/Subscriptions	14	-	-
Income from Investments for earmarked/endowment funds)	15	-	-
Income from Royalty	16	-	-
Interest Earned	17	84,62,017	28,25,167
Other Income	18	67,60,017	15,09,731
Increase/Decrease in stock of finished goods	19	-	-
TOTAL (A)		**52,40,03,602**	**45,41,58,091**
EXPENDITURE			
Establishment Expenses	20	31,78,54,433	24,97,09,368
Other Administrative Expenses	21	12,97,96,369	11,38,60,765
Expendtiture on Grants/Subsidies	22	-	-
Interest	23	-	-
Depreciation (Net as per Schedule 8)		6,51,86,568	6,17,74,193
TOTAL (B)		**51,28,37,370**	**42,53,44,326**
INTEREST ON GRANT BALANCES TRF TO BHARATKOSH - Sch 7(A)(1b)		**22,82,539**	**-**
BALANCE-SURPLUS/(DEFICIT) CARRIED TO CORPUS/CAPITAL FUND - Sch. 1(2b)		**88,83,693**	**2,88,13,765**
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
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Sd/-
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(Gopalkrishna Hegde)
Partner
M No. 208063

BENGALURU / 4th July 2019

RAMAN RESEARCH INSTITUTE, BENGALURU
RECEIPTS AND PAYMENTS STATEMENT FOR THE YEAR ENDED 31ST MARCH 2019

(Amount in INR)

RECEIPTS	Current Year	Previous Year	PAYMENTS	Current Year	Previous Year
I. Opening Balances			**I. Expenses**		
a) Cash in hand	-	-	a) Establishment Exp	31,78,54,433	21,24,83,972
b) Bank Balances	2,37,06,854	1,59,60,630	b) Admin Expenses	12,84,72,101	2,60,09,351
c) Deposits	25,57,33,900	21,51,89,105	c) PF-Final Settlement	78,97,135	67,70,880
d) Stamps (Franking M/C)	966	1,582	d) Pension Payout	-	-
II. Grants Received			**II. Payments made against projects**	2,68,16,173	3,73,65,648
a) From Govt. of India	48,81,60,000	46,85,72,000			
b) From State Govt.	-	-	**III. Investment and deposits made**		
c) From other sources	8,61,87,555	7,28,41,877	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**	4,22,88,842	8,91,05,822
b) Own Funds	-	-			
			V. Refund of surplus money / loans		
IV. Interest Received			a) To Govt. of India	-	-
a) On Bank deposits	2,20,56,391	1,46,02,797	b) To State Govt	-	-
b) on Loans, Advances etc.	3,02,272	1,962	c) To other fund providers	-	-
V. Other Income (Specify)	70,46,848	-	**VI. Finance charge (Interest)**	-	-
VI. Amount Borrowed	-	-	**VII. Other Payments (Specify)**	-	-
VII. Any other Receipts (Specify)			a) TDS Receivable	8,42,890	4,35,550
a) Advances	20,18,400	2,06,68,199	b) Advances	25,25,734	2,38,900
b) Receivables	1,69,10,881	40,86,938	c) Investments (Nett)	-	2,18,985
c) Accrued Interest	10,94,118	4,75,729	d) EMD, SD, CD (Deposits)	12,57,184	18,60,450
d) Investments (Nett)	37,912	9,64,717	e) Bills Payable	29,36,010	12,51,54,772
e) Overheads	4,65,320	21,76,118	f) Payroll Recoveries	3,14,66,711	3,77,19,944
f) Deposits	8,40,000	-	g) Deposits (for services)	-	21,000
g) Pension Corpus	35,71,204	-	h) Duties & Taxes	13,41,016	14,25,850

RAMAN RESEARCH INSTITUTE, BENGALURU
RECEIPTS AND PAYMENTS STATEMENT FOR THE YEAR ENDED 31ST MARCH 2019

(Amount in INR)

RECEIPTS	Current Year	Previous Year	PAYMENTS	Current Year	Previous Year
h) Employees's subscription	1,80,01,300	1,65,22,100	i) Provision	13,11,739	14,47,868
			j) PF-Withdrawals	94,93,000	1,00,53,600
			h) CPF (Emplyr Share)-Trf to Pension	27,49,573	23,09,442
			VIII. Closing Balances		
			a) Cash Balance	281	-
			b) Bank Balances		
			i) Deposit Accounts	33,06,96,492	25,57,33,900
			II) Current/Savings Account	1,81,70,200	2,37,06,854
			c) Postal franking machine	14,407	966
TOTAL	**92,61,33,921**	**83,20,63,754**		**92,61,33,921**	**83,20,63,754**

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

Sd/-
(C. S. R. Murthy)
Administrative Officer

Sd/-
(Ravi Subrahmanyan)
Director

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

BENGALURU / 4th July 2019

RAMAN RESEARCH INSTITUTE, BENGALURU
SCHEDULES FORMING PART OF BALANCE SHEET AS AT 31ST MARCH 2019

(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	107,46,27,894		104,72,88,885	
Addition during the year	11,66,83,147		14,09,17,761	
Less: Deductions during the year *(Includes Capital Work-in-progress)*	7,43,94,305		5,18,04,559	
Less: Depreciation chargeable transferred to Income and Expenditure A/c	6,51,86,568		6,17,74,193	
BALANCE AS AT THE YEAR END		105,17,30,168		107,46,27,894
(2) GRANT BALANCES				
(a) NON-RECURRING GRANT				
Balance as at the beginning of the year		35,95,767		1,16,31,109
Add: Contributions during the year	4,45,65,000		8,05,23,000	
Add: Interest earned on LC Margin Money & Term Deposits	-	4,45,65,000	5,54,860	8,10,77,860
Less: Expenditure incurred during the year		4,22,88,842		8,91,13,202
BALANCE AS AT THE YEAR END		58,71,925		35,95,767
(b) RECURRING GRANT				
Balance as at the beginning of the year	(1,03,94,457)		(3,92,08,222)	
Transferred from Income & Expenditure-	88,83,693		2,88,13,765	
-Account for the year				
BALANCE AS AT THE YEAR END		(15,10,764)		(1,03,94,457)
TOTAL (1+2)		**105,60,91,329**		**106,78,29,204**

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 2019

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 31/03/19
					Capital Expenditure	Recurring Expenditure	Advances/ Receivables		
Funded by Government Agencies									
1	CSIR	Dr. Bhatnagar Award-Dr. Sadiq Rangwala	-	1,80,000	-	1,80,000	-	1,80,000	-
2		Dr. Bhatnagar Award-Prof Deshpande	-	1,80,000	-	1,80,000	-	1,80,000	-
3	DAE	Prof. Krishnakumar-RRF-DAE	-	13,50,000	-	8,70,968	-	8,70,968	4,79,032
4	DBT	Biomechanics of Synaptogesis-Dr Pramod	7,321	-	-	-	-	-	7,321
5		Joint Project-Dr. Pramod	-	20,57,000	-	18,90,237	-	18,90,237	1,66,763
6		Ramalingaswamy Fellowship- Dr. Gautam	(5,18,142)	5,00,000	-	-	-	-	(18,142)
7	DST	DST-MWA Project- Prof Shiv Sethi	36,269	-	-	-	-	-	36,269
8		Ramanujan Fellowship- Dr Pramod	2,06,447	-	-	-	-	-	2,06,447
9		Indo-Aus BMWF Jt. Research	70,579	-	-	-	-	-	70,579
10		Indo-Aus Strategic Res. Fund- Dr Reji	(4,820)	-	-	-	-	-	(4,820)
11		Indo-Russia Joint Project- Prof Biman Nath	4,73,600	-	-	4,73,600	-	4,73,600	-
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-Indoltaly-Dr. Urbasi	-	57,03,520	-	3,45,320	-	3,45,320	53,58,200
15		DST-BRICS-Travel-Dr. Hema	2,85,436	-	-	2,85,436		2,85,436	-
16	IFCPAR	CEFIPRA Grant- Prof Hema R	1,37,525	-	-	-	-	-	1,37,525
17		CEFIPRA Grant- Dr. Sadiq Rangwala	(19,921)	7,92,800	-	9,59,530	-	9,59,530	(1,86,651)
18	ISRO	ISRO-Polix Project-Prof Biswajit	5,38,757	-	-	5,38,757	-	5,38,757	-
19		PRATUSH-Dr. Mayuri	-	36,00,000	-	-	-	-	36,00,000
20		ISRO-Polix Payload-Prof Biswajit	49,00,306	1,72,86,946	3,23,37,466	-	(3,75,00,000)	(51,62,534)	2,73,49,786
21		ISRO-QKD-Project-Dr. Urbasi	2,24,83,248	4,49,25,340	55,83,707	59,46,324	43,64,513	1,58,94,544	5,15,14,044
22	IUSSTF	IUSSTF Grant-Prof Shiv	5,17,502	-	-	14,922	-	14,922	5,02,580
23	SERB	Ramanujan Fellowship- Dr Sayantan	-	7,60,000	-	7,63,144	-	7,63,144	(3,144)
24		TARE Grant- Dr. Anoop, CUSAT	-	3,35,000	-	-	-	-	3,35,000
25		Ramanujan Fellowship- Dr Uma Basu	-	7,60,000	-	1,60,073	-	1,60,073	5,99,927
26		Vajra Fellowship-Prof Satya Majumdar	-	10,86,300	-	10,79,837	-	10,79,837	6,463
27		Vajra Fellowship-Prof Sanders	-	11,45,700	-	10,35,370	-	10,35,370	1,10,330
28		Inspire Fellowship-Dr. Saurav Datta	(9,67,171)	9,67,171	-	-	-	-	-
29		Ramanujan Fellowship-Dr. Dibyendu	7,20,398	20,00,000	-	17,28,867	-	17,28,867	9,91,531

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 31/03/19
					Capital Expenditure	Recurring Expenditure	Advances/ Receivables		
30	TIFR	TIFR-Grant-Prof. Krishnakumar	91,549	-	-	35,957	-	35,957	55,592
SUB TOTAL			**2,94,41,483**	**8,36,29,777**	**3,79,21,173**	**1,64,88,342**	**(3,31,35,487)**	**2,12,74,028**	**9,17,97,232**
Funded by other than Government Agencies									
1	IKP	GCE Grant-Dr. Gautam Soni	18,03,728	57,581	13,77,005	19,19,526	-	32,96,531	(14,35,222)
2	CNRS	CNRS-Dr. Urbasi Sinha	(1,97,002)	24,42,616	-	22,45,614	-	22,45,614	-
SUB TOTAL			**16,06,726**	**25,00,197**	**13,77,005**	**41,65,140**	-	**55,42,145**	**(14,35,222)**
Retirement Funds									
1	-	Gratuity Fund	6,65,18,296	49,91,804	-	74,67,206	-	74,67,206	6,40,42,894
2		Leave Salary Fund	5,50,10,403	41,76,720	-	45,71,101	-	45,71,101	5,46,16,022
3		Pension Commutation Fund	20,97,35,745	1,62,06,314	-	70,31,629	-	70,31,629	21,89,10,430
4		RRI Pension Fund	9,36,84,740	84,13,557	-	77,13,012	-	77,13,012	9,43,85,285
5		RRI Provident Fund	13,89,79,044	1,91,59,556	-	95,21,366	-	95,21,366	14,86,17,234
SUB TOTAL			**56,39,28,228**	**5,29,47,951**	-	**3,63,04,314**	-	**3,63,04,314**	**58,05,71,865**
GRAND TOTAL			**59,49,76,437**	**13,90,77,925**	**3,92,98,178**	**5,69,57,796**	**(3,31,35,487)**	**6,31,20,487**	**67,09,33,875**

RAMAN RESEARCH INSTITUTE, BENGALURU
SCHEDULES FORMING PART OF BALANCE SHEET AS AT 31ST MARCH 2019

(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	-		-	
b) Others **(Includes earnings to be transferred to BHARATKOSH)**	37,82,013	37,82,013	1,66,878	1,66,878
2. Earnest Money Deposit		8,43,000		21,90,000
3. Advances Received		1,00,00,000		1,02,13,898
4. Statutory Liabilities				
a) Overdue				
b) Others	-		-	
5. Other Current Liabilities (Incl. Security Deposit)	38,75,910	38,75,910	22,49,480	22,49,480
TOTAL (A)		**1,85,00,923**		**1,48,20,256**
B. PROVISIONS				
1. Gratuity	1,41,756		1,41,756	
2. Superannuation / Pension	2,70,939		1,94,970	
3. Accumulated Leave Encashment	-		-	
4. Others (Specify)	44,74,101		37,44,550	
TOTAL (B)		**48,86,796**		**40,81,276**
TOTAL (A+B)		**2,33,87,719**		**1,89,01,532**

RAMAN RESEARCH INSTITUTE, BENGALURU
SCHEDULES FORMING PART OF BALANCE SHEET AS AT 31ST MARCH 2019

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	18,03,33,777	1,04,92,399	-	19,08,26,176	3,58,08,417	30,77,653	-	3,88,86,070	15,19,40,106	14,45,25,360
3. Canteen Infrastructure	4.75	43,68,271	15,669	-	43,83,940	16,33,652	2,08,121	-	18,41,773	25,42,167	27,34,619
4. Plant Machinery, Equipment	4.75	96,83,15,329	4,31,82,510	-	101,14,97,839	42,58,30,990	4,79,44,051	-	47,37,75,041	53,77,22,798	54,24,84,339
5. Vehicles	9.50	74,51,930	-	-	74,51,930	60,70,115	7,07,933	-	67,78,048	6,73,882	13,81,815
6. Furniture & Fixtures	6.33	1,49,47,646	3,20,810	-	1,52,68,456	1,00,55,168	9,63,350	-	1,10,18,518	42,49,938	48,92,478
8. Computer Peripherals	16.21	16,18,32,087	41,28,738	-	16,59,60,825	15,52,20,844	13,49,780	-	15,65,70,624	93,90,201	66,11,243
9. Library Books	4.75	22,98,60,252	5,20,191	-	23,03,80,443	13,29,30,859	1,09,35,680	-	14,38,66,539	8,65,13,904	9,69,29,393
Total Fixed Assets		**165,06,70,724**	**5,86,60,317**	**-**	**170,93,31,041**	**76,75,50,045**	**6,51,86,568**	**-**	**83,27,36,613**	**87,65,94,428**	**88,31,20,679**
B. Work in Progress											
Capital Assets		3,79,30,327	4,63,69,535	3,77,58,417	4,65,41,445	-	-	-	-	4,65,41,445	3,79,30,327
Total Capital Work in Progress		**3,79,30,327**	**4,63,69,535**	**3,77,58,417**	**4,65,41,445**	**-**	**-**	**-**	**-**	**4,65,41,445**	**3,79,30,327**
Grand Total		**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**
Previous Year		**164,14,70,917**	**9,89,34,693**	**5,18,04,559**	**168,86,01,051**	**70,57,75,852**	**6,18,49,220**	**75,027**	**76,75,50,045**	**92,10,51,006**	**93,56,95,065**

RAMAN RESEARCH INSTITUTE, BENGALURU
SCHEDULES FORMING PART OF BALANCE SHEET AS AT 31ST MARCH 2019

(Amount in INR)

Schedule 9- Investments from Earmarked/Endowment Funds	Current Year	Previous Year
1. In Fixed Deposits		
RRI Pension Fund	9,51,18,276	8,88,74,375
RRI Provident Fund	13,10,59,525	12,75,59,525
Other Grants & Funds	9,62,00,000	2,93,00,000
2. Other Approved Securities	-	-
3. Shares	-	-
4. Debentures / Bonds	-	-
5. Subsidiaries and Joint Ventures	-	-
6. Retirement funds invested in SBI Life Insurance Limited	33,75,69,346	33,12,64,444
TOTAL	**65,99,47,147**	**57,69,98,344**

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 2019

(Amount in INR)

Schedule 11- Current Assets, Loans & Advances	Current Year		Previous Year	
A. CURRENT ASSETS				
1. Inventories		10,75,768		8,10,114
2. Cash balances in hand (Including cash imprest)		281		-
3. Unused stamp value on Postal Franking Machine		14,407		966
4. Bank Balances				
Main Account				
In Current Accounts	30,05,599		1,07,96,267	
In Savings Bank Account	9,55,302	39,60,901	17,36,255	1,25,32,522
Pension Fund Account				
In Current Accounts	11,89,092		16,66,969	
In Savings Bank Account	2,31,104	14,20,196	2,23,761	18,90,730
Provident Fund Account				
In Current Accounts	1,02,11,267		68,97,264	
In Savings Bank Account	8,96,527	1,11,07,794	7,62,610	76,59,874
Extra Mural Grants				
In Savings Bank Account	16,81,309	16,81,309	16,23,728	16,23,728
TOTAL (A)		**1,92,60,656**		**2,45,17,934**
B. LOANS/ADVANCES AND OTHER ASSETS				
1. Advances and other amounts recoverable in cash				
On Capital Account				
a) Land	9,25,90,600		6,89,61,800	
b) Capital Assets	1,16,53,295	10,42,43,895	4,19,83,068	13,09,44,868
Deposits		36,33,632		41,78,632
Others		1,29,43,302		72,23,598
2. Income Accrued				
Main Account	31,66,062		13,69,632	
Provident Fund Account	29,20,069		8,11,567	
Pension Fund Account	45,42,923	1,06,29,074	22,44,909	44,26,108
3. Claims Receivable				
Main Account	14,76,302		6,58,266	
Extra Mural Grants	27,53,620		1,80,000	
Provident Fund Account	13,42,147		8,53,671	
Pension Fund Account	10,47,275	66,19,344	6,74,726	23,66,683
TOTAL (B)		**13,80,69,247**		**14,91,39,889**
TOTAL (A+B)		**15,73,29,903**		**17,36,57,823**

RAMAN RESEARCH INSTITUTE, BENGALURU

SCHEDULES FORMING PART OF INCOME & EXPENDITURE ACCOUNT FOR THE YEAR ENDED 31ST MARCH 2019

(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)	6,51,86,568	6,17,74,193
iii) Plan-Recurring	44,35,95,000	38,80,49,000
Total	**50,87,81,568**	**44,98,23,193**

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	4,46,09,763	3,92,33,372
Less: Transferred to Earmarked / Endowment Fund	4,46,09,763	3,92,33,372
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)**	22,82,539	-
b) Attributable to Own/other funds	58,77,206	26,76,468
3) On Loans/Advances		
a) Employees	3,02,272	1,48,699
Total	**84,62,017**	**28,25,167**

RAMAN RESEARCH INSTITUTE, BENGALURU

SCHEDULES FORMING PART OF INCOME & EXPENDITURE ACCOUNT FOR THE YEAR ENDED 31ST MARCH 2019

(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	67,60,017	15,09,731
Total	**67,60,017**	**15,09,731**

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	13,64,49,714	9,54,91,595
b) Allowances & Bonus	7,71,25,837	9,28,48,301
c) Contrbution to Provident Fund	-	14,49,509
d) Contribution to NPS	34,35,021	30,61,808
e) Staff welfare expenditure	1,32,45,661	1,03,23,131
f) Retirement/Terminal benefits	8,75,98,200	4,65,35,024
Total	**31,78,54,433**	**24,97,09,368**

Schedule 21- Other administrative expenses	Current Year	Previous Year
1) Advertisement	2,30,089	5,32,521
2) Amenities	19,79,524	19,91,180
3) Audit Fee	64,900	78,200
4) Bank Charges	2,15,613	46,489
5) Campus Maintenance	1,66,22,707	1,67,45,656
6) Conveyance	4,34,321	4,80,577
7) Corporation Taxes	2,70,574	2,41,386
8) Creche	3,00,000	3,00,000
9) Electricity Charges	1,36,10,904	1,33,80,924

Continued on the next page

Schedule 21- Other administrative expenses (Continued)	Current Year	Previous Year
10) Entertainment & Hospitality	67,056	1,62,251
11) Freight	4,07,659	4,33,254
12) Honorarium & Professional Fee	60,26,841	55,18,324
13) Journal Subscription	22,27,289	33,76,703
14) Lease Rent (Gauribidanur)	5,23,492	4,70,830
15) Miscellaneous Expenses	14,51,469	7,02,723
16) Outreach	11,97,610	11,63,036
17) Patent Fee	4,71,500	3,14,500
18) Payroll Processing Charges	4,14,430	4,68,156
19) Ph.D Programme Expenditure	16,89,778	13,19,763
20) Postage & Courier Charges	1,31,376	1,62,468
21) Printing & Stationery	3,99,611	10,29,939
22) Repairs & Maintenance	79,63,096	1,12,82,304
23) Security Charges	89,59,296	93,82,335
24) Seminar/Conference	12,68,710	12,07,940
25) Stores & Consumables	4,43,42,105	2,65,48,542
26) Telephone & Communication	15,25,933	15,33,871
27) Travel Expenditure	90,72,250	73,14,681
28) Uniform & Livery	2,29,194	90,464
29) University Affiliation Fee	6,00,000	6,00,000
30) Vehicle Maintenance	24,71,382	26,37,557
31) Visiting Students Programme	39,14,740	35,70,795
32) Water Charges	7,12,920	7,73,396
Total	**12,97,96,369**	**11,38,60,765**

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

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

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 Anton Paar, Austria towards procurement of instruments This LC would be retired in FY20
2.	Bank guarantees given by the Institute	NIL
3.	Disputed demands in respect of taxes	An amount of **Rs. 3,55,670/-** 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 Commutted value of Pension is through the fund. d. In pursuance of the directions of the Council, the amount representing Institute's contribution to the CPF in respect of eligible Senior Scientific and Technical staff members (who joined the Institute before 01/01/2004) on

contractual terms are allowed to exercise an option to opt for the Institute's pension scheme, on periodic renewal of their contracts for continuous engagement in the Institute upto superannuation. PF balances standing to the credit of such members is transferred to the Pension corpus. The income generated on the corpus is used to partially fund the pension liability. Deficit, if any, is met out of regular grants-in-aid.

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

3. Advance for purchase of land

The Institute has deposited **Rs. 8,89,61,800/-** with M/s Hindustan Machine Tools Limited, being full value of a land, in pursuance of a sale agreement entered into between the Institute and HMT Limited on **13th March 2009.** The 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. 22,82,539/-** 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 2019 and the Income & Expenditure Account for the year ended on that date.

6. Following the changeover in financial reporting as per Uniform Format of Accounts, numbers pertaining to the previous years have been regrouped and rearranged to conform to current year figures

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

Sd/-
(C. S. R. Murthy)
Administrative Officer

Sd/-
(Ravi Subrahmanyan)
Director

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

BANGALORE / 4th July 2019

For further information, please write to
The Director
Raman Research Institute
C. V. Raman Avenue
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