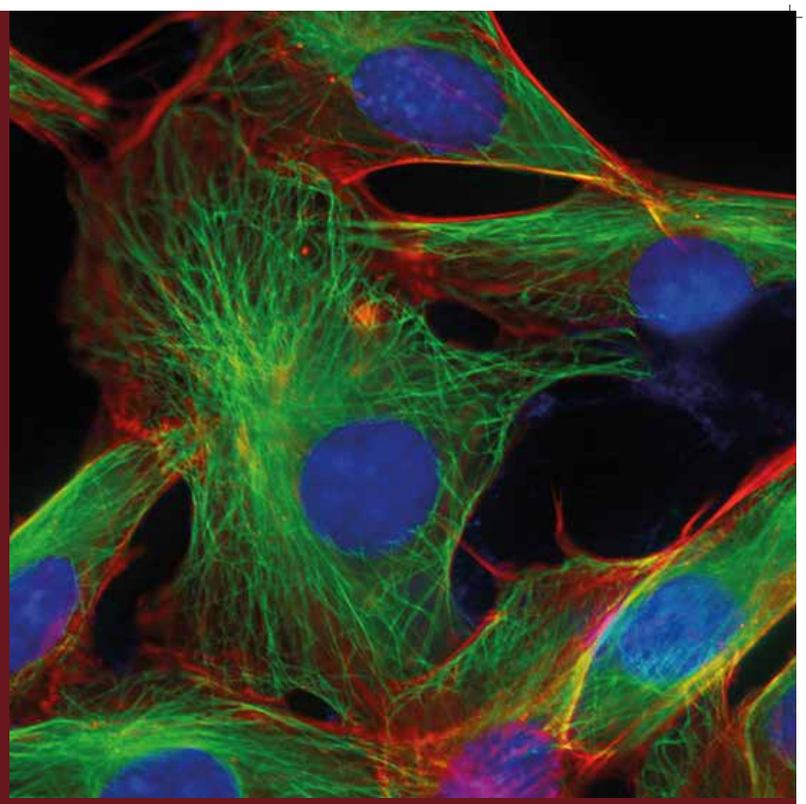
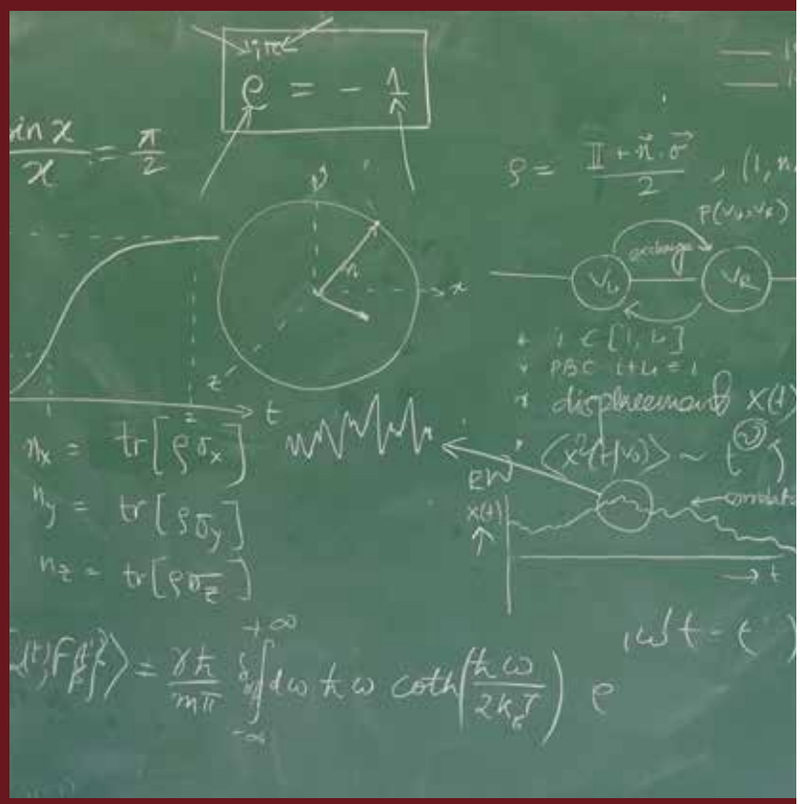
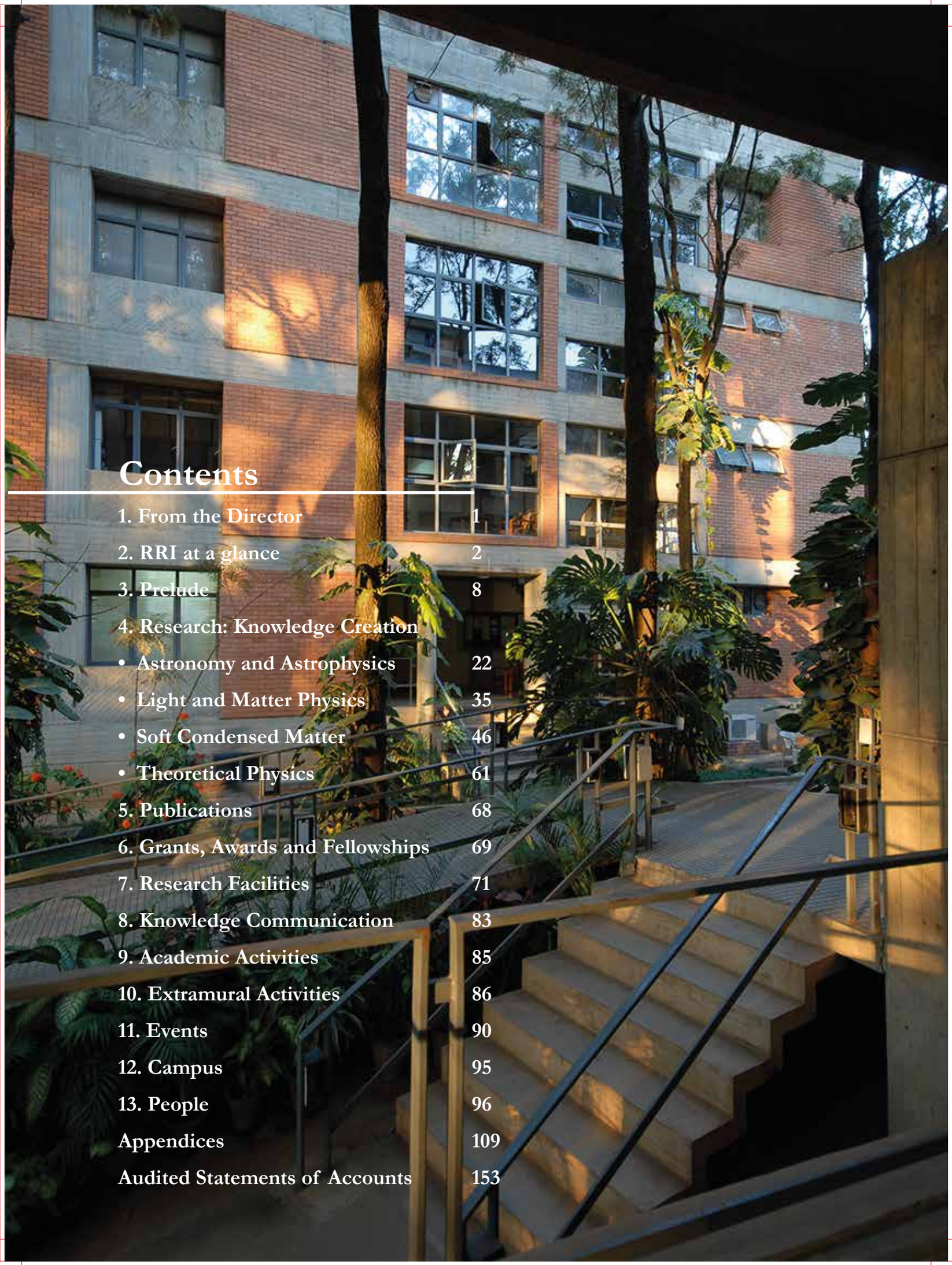




RRI

RAMAN RESEARCH INSTITUTE
BENGALURU

Annual Report 2016 - 2017



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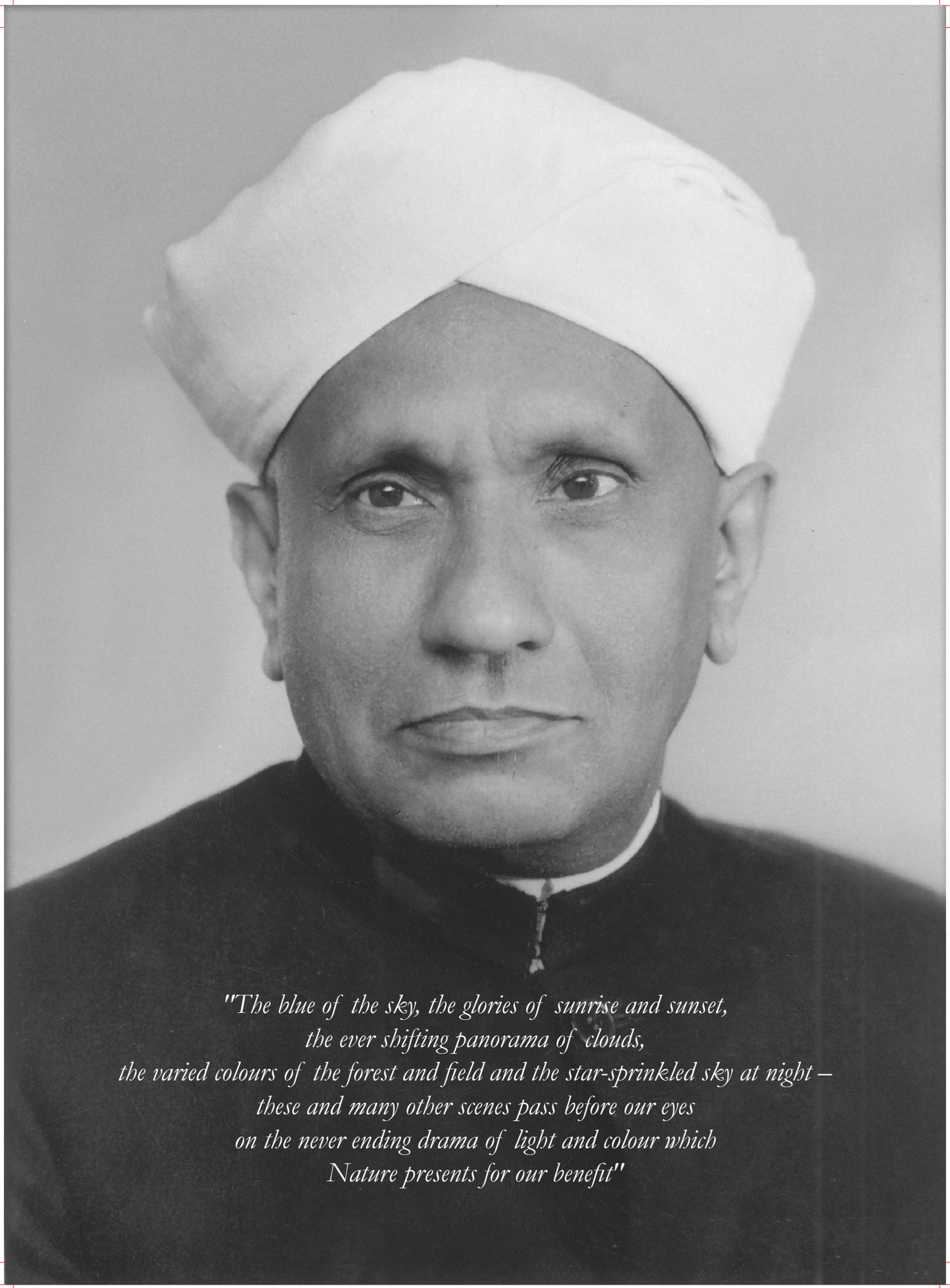

"The blue of the sky, the glories of sunrise and sunset,
the ever shifting panorama of clouds,
the varied colours of the forest and field and the star-sprinkled sky at night –
these and many other scenes pass before our eyes
on the never ending drama of light and colour which
Nature presents for our benefit"

From the Director

We were delighted to welcome a visit of the Parliamentary Standing Committee on Science and Technology, Environment and Forests. Chaired by Honourable Member of Parliament, Smt. Renuka Chowdhury, the committee spent a whole afternoon and evening at the Institute in August 2016, hearing of the highlights of ongoing research and future visions, seeing the activity in the laboratories, experiencing the campus, and finally joining the members of the Institute for a high tea in a regal dining setting with free flowing conversations with students and staffs and choice foods befitting the occasion. The visit was special to us and a special effort was made by one and all at the Institute to make the visit memorable for the Honourable Parliamentarians.

In December 2016, the Institute made another special and noteworthy effort, to reach out and communicate our research to the public by creating a distinctive eye-catching stall at the 2nd India International Science Festival in New Delhi, in which poster panels and hands-on exhibits showcased our creativity and innovations in modern times as well as the historical inspiration of our Founder, Sir C V Raman. We were happy to receive the award for the best stall at the event from the Honourable Minister Dr Harsh Vardhan himself.

The year 2016-17 was one in which the Institute engaged in many discussions aimed at better defining its future, by working towards vision documents and holding open-forum "Futures Discussions" that provided opportunity for young and old to present their aspirations and dreams.

We at the Institute are clear that the Raman Research Institute is a premier research institute with a mandate to engage in fundamental research in basic sciences, and that is certainly our vision for the future. While we aim to provide a nurturing environment for individual excellence in chosen areas in the research landscape, in theory and experiment, and while we aim to share our advanced knowledge and research passion and skills with the younger generation who join us in our adventures in science, we also aim to cultivate a few small teams to work collectively on a few key research problems in which we may have an unfair advantage given our history and inherent strengths. In the coming few years, we have dreams of leading a research in X-ray astronomy with the flight of our POLIX payload on ISRO's XPoSat mission; we have dreams of participating in the next step of exploration into the transient and dark universe on the wings of SWAN and SARAS and MWA and SKA, along with efforts to advance basic research in key problems of quantum communications and DNA sequencing, which are obviously foundational to the security and well-being of future societies.

Ravi Subrahmanyan
26 Aug 2017

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, 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 today is 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 & Re-ionization 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
- Liquid Crystal Display
- Microscopy and Dielectric Spectroscopy
- Nanoscale Physics of Soft and Living Matter
- Brain Computer Interface

Research Facilities

Soft Matter Measurement Laboratories

- Analytical Physical Measurement Lab
- X-ray Diffraction Lab
- Scanning Electron Microscopy Lab
- Atomic Force Microscopy Lab
- Nuclear Mannetic Resonance Spectroscopy 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
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 AK Sood, *Chairman*
Department of Physics, Indian Institute of Science, Bengaluru 560 012

Dr K Kasturirangan
Chancellor, Jawaharlal Nehru University, New Mehrauli Road, New Delhi 110 067

Prof PK Kaw
Senior Professor & Distinguished Scientist, Institute of Plasma Research, Gandhinagar 382 428

Prof. Ashutosh Sharma
Secretary, Department of Science & Technology, Ministry of Science & Technology, New Delhi 110 016

Shri JB Mohapatra
Joint Secretary & Financial Advisor, Ministry of Science & Technology, Government of India, New Delhi 110 016

Prof R Rajaraman
Emeritus Professor, Theoretical Physics, School of Physical Sciences, Jawaharlal Nehru University, New Delhi 110 067

Prof. Vijay Bhatkar
Chairman, ETH Research Lab, Bavdhan, Off Mumbai-Bengaluru Bypass, Pune 411 021

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

Finance Committee

Prof AK Sood, *Chairman*
Department of Physics, Indian Institute of Science, Bengaluru 560 012

Shri JB Mohapatra
Joint Secretary & Financial Advisor, Ministry of Science & Technology, Government of India, New Delhi 110 016

Prof. PK Kaw
Senior Professor & Distinguished Scientist, Institute of Plasma Research, Gandhinagar 382 428

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

Academic Committee

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

Prof. Bupinder Zutshi
Director of Admission/Controller of Examinations, Jawaharlal Nehru University, New Delhi 110 067

Prof. Gautam Menon
Institute of Mathematical Sciences, C.I.T Campus, 4th Cross St,Taramani Chennai, Tamil Nadu 600 113

Prof. Sharath Ananthamurthy
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Prof. Subhasish Ghosh
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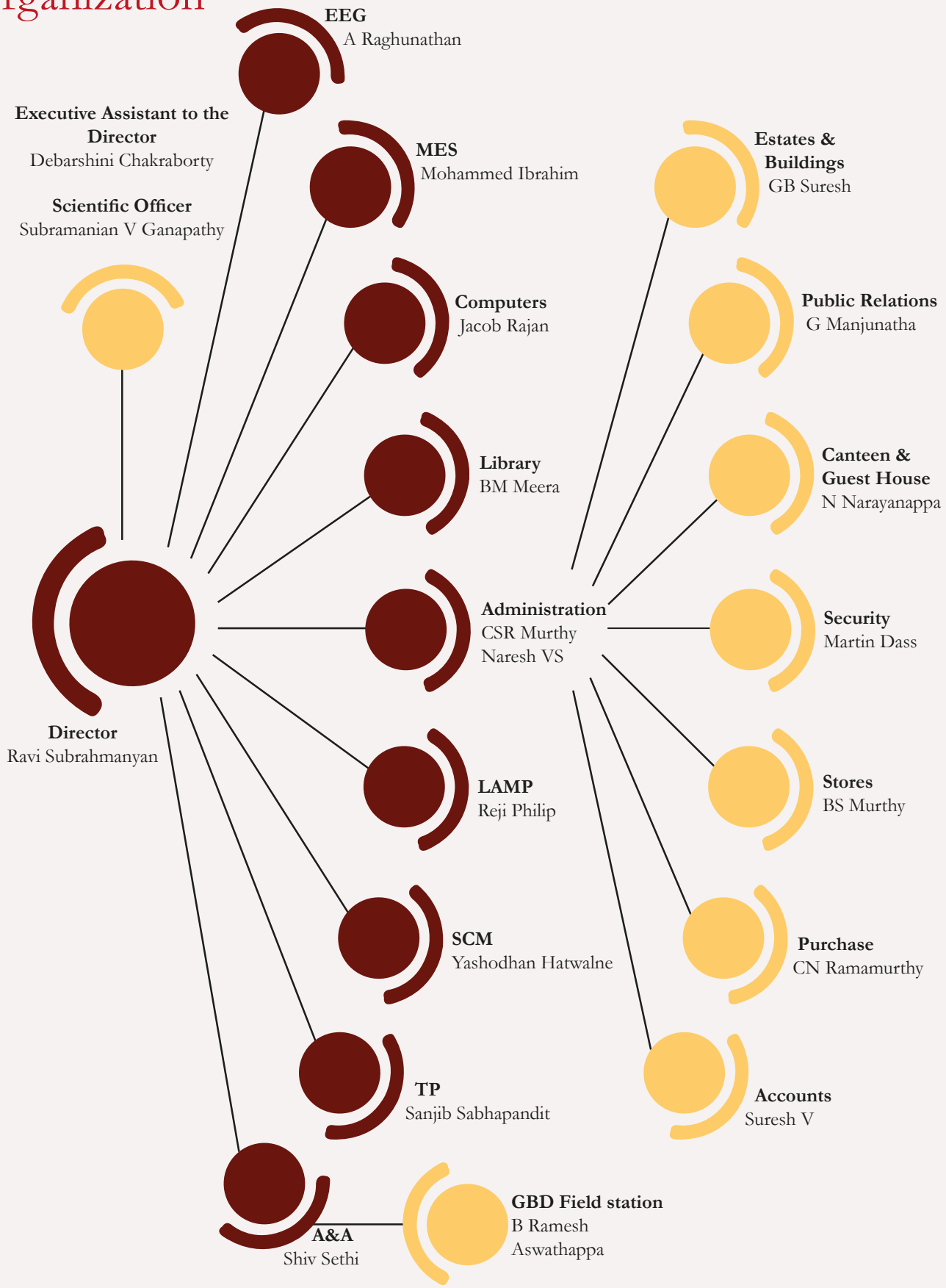
Soft Condensed Matter Group, Raman Research Institute, C.V.Raman Avenue, Sadashivanagar, Bengaluru 560 080

Dr. Ranjini Bandopadhyay
Soft Condensed Matter Group, Raman Research Institute, C.V.Raman Avenue, Sadashivanagar, Bengaluru 560 080

Mr. C.S.R. Murthy
Administrative Officer, Raman Research Institute, C.V.Raman Avenue, Sadashivanagar, Bengaluru 560 080

Organization



Committees

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

Admission Coordinators

Sanjib Sabhapandit, Pramod Pullarkat

SAAC

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

In-House meeting

PhD students – 3rd year

JAP Rep of RRI

S Sridhar

Complaints Committee

Srivani (Chairperson), BM Meera, CSR Murthy, Madan Rao,
Mamatha Bai

Overseas Travel Commitee

Biswajit Paul (Chairperson), Reji Philip, Pratibha R

Evaluation Committee

Dwarakanath KS (Chairperson), Joseph Samuel,
Biman Nath, VA Raghunathan, Sadiq Rangwala

Academics & Research Committee

Joseph Samuel (Chairperson), Hema Ramachandran,
Biman Nath

Coordinator of Visiting Students Programme

CSR Murthy

Library Committee

BM Meera (Chairperson), Yashodhan Hatwalne,
Supurna Sinha, Reji Philip, Nayantara Gupta

RRI Official Language
Implementation Committee

CSR Murthy (Chairperson), Suresh Varadarajan,
Ranjeet Koshta, R Ramesh, CN Ramamurthy,
B Srinivasamurthy. BM Meera, G Manjunatha,
K Radhakrishna, VVidyamani, Harini Kumari,
Mamatha Bai, Jacob Rajan, Naresh VS

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 eminent scientific personalities who have worked in National Institutions 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 learning and scientific temper, 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 the 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 the 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 providing 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 from both Indian and overseas universities. 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 more details on the various programs that ensure a steady stream of top quality research manpower for our country the reader may visit the knowledge communication 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. For a complete list see Appendices III and IV.

Astronomy and Astrophysics (AA)

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) The third aspect involves the design, construction and operation of telescopes, which are often built for very specific purposes, and are strategically located around the world and in space.

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

Focus 2016-17

Theoretical Astrophysics

One could not be faulted for staring at the starry sky and coming to the conclusion that we live in a more or less static universe and nothing interesting is going on "up there". However, nothing could be farther from the truth. The Universe is actually a very vibrant place where various dynamic processes occur on all length scales from stars to galaxies to galaxy clusters and beyond that shape their evolution. Stars are born, evolve, eject gases into the atmosphere (stellar winds), and eventually some of them end their lives in spectacular explosions called supernovae. A combination of stellar winds, black hole jets and or shock waves from supernova explosions result in a shell of interstellar gas known as bubbles and super-bubbles. Galaxies in clusters merge with other galaxies, some display a very high rate of star formation (starbursts) and most harbor supermassive black holes at their centers. Detailed theoretical studies shed light on these processes and add to the knowledge base of our understanding of the Universe. The sections below are structured as follows – a brief introduction to each of these topics is provided followed by an executive summary of the research that falls under the topic. More detailed description of the research is provided further down in this Annual Report.

Intracluster medium and Galactic outflows:

AA group members and collaborators have analyzed data from a sample of galaxy clusters and shown evidence for the first time that rules out models of "preheating" in intracluster gas at the outer regions that are least affected by cooling and active galactic nuclei (AGN) feedback from the central region. With detailed analytical calculations and 1D hydrodynamic simulations RRI researchers have found that radiation pressure is important in the early period after the onset of star formation in a cluster after which heating due to radiation becomes important. They have also studied the evolution of clustered supernovae to form a single bubble and provide observational diagnostics that will help observers to distinguish this phase of evolution of super-bubbles. Recent research has worked out the basic physical process and the parameters that can support molecule formation in starburst nuclei (the highly dense central region of a starburst galaxy). Using the recently determined OVII/OVIII line ratio RRI researchers have discriminated between bubbles driven by star formation and by black hole jets and estimate the age for the bubbles as 15-20 million years.

Stellar Dynamics in Galactic nuclei:

In the recent past researchers at RRI have developed a theory that provides firm foundations for the dynamical and statistical mechanical theory of Keplerian stellar systems (whose mass is smaller than the mass of their black holes). Over the past year, they have demonstrated the power of the theory by applying it to model problems regarding the dynamics and statistical mechanics of astrophysical disks including the response of a stellar, spherical density cusp at the galactic center, to a growing ring of gas.

Cosmology:

During the past year cosmologists at RRI have proposed a general method, based on the delay spectrum approach, to extract HI power spectra that is applicable to tracking observations using an imaging radio interferometer. They have also investigated the possibility of using the Silk-damping induced CMB spectral distortion as a probe of the small-scale power in four suggested alternative dark matter candidates and have obtained interesting results.

Theoretical modeling of astrophysical sources:

Astrophysicists at RRI have, in the year, explored high energy and very high energy phenomena in the universe with gamma ray, neutrino and cosmic ray data and have theoretically interpreted the observational results and provided estimates to the jet power related to synchrotron emission of electrons and protons.

Observational Astronomy

It would come as a surprise to many if you tell them that what the human eye sees of the night sky is just a very small portion of what is really coming to us from the heavens above. The reason being that the human eye is sensitive to just one small portion of the much larger panorama called the electromagnetic spectrum, which includes gamma rays, x-rays, ultraviolet, microwave and radio waves. On a fundamental

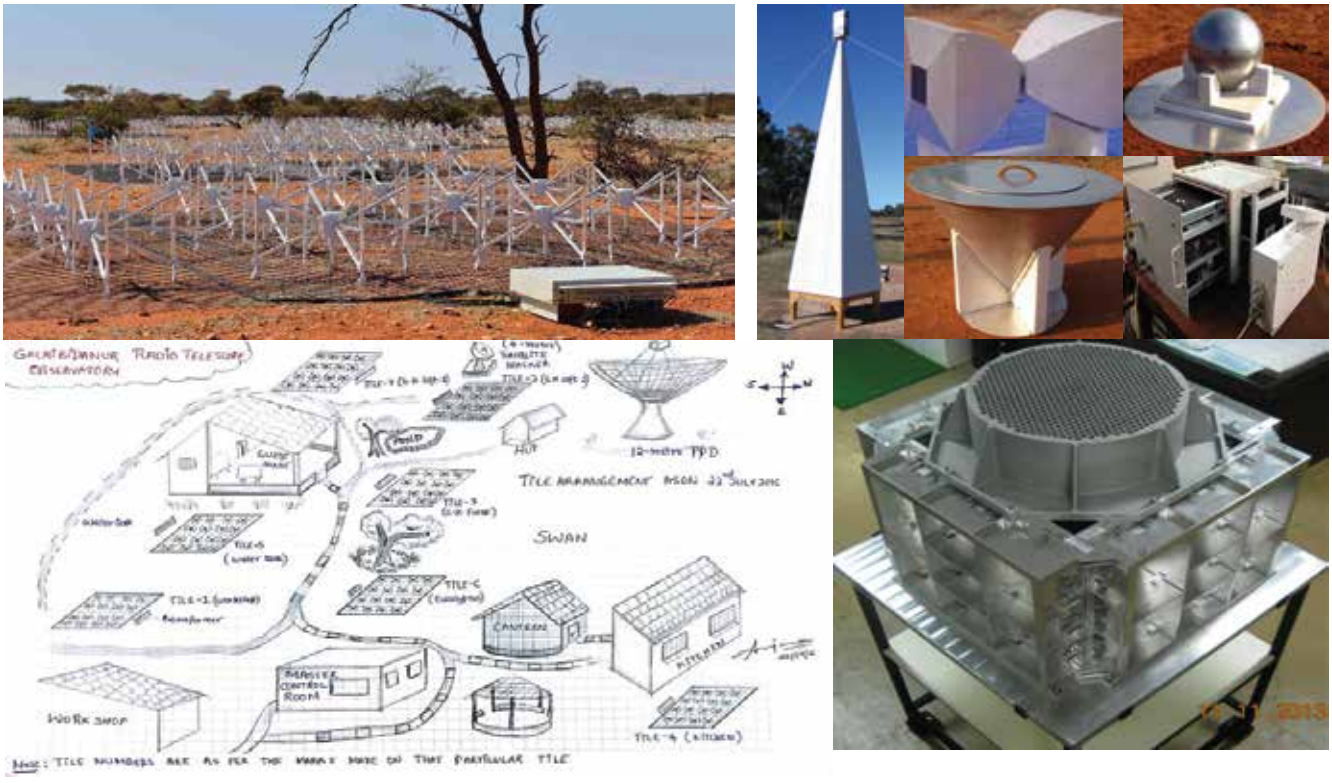
level the above different forms of radiation are all the same, the difference lies in the frequency and wavelengths of the electromagnetic signal. The universe talks to us over the entire electromagnetic spectrum and the innate curiosity of the human mind would want to devise ways to listen. Astronomers have in fact built specialized telescopes designed to "see" in different frequency bands of radiation. RRI has been involved in designing and constructing Radio and X-ray telescopes both nationally and internationally - for example the Murchison Widefield Array, a precursor to the SKA telescope, which is a megaproject of the nation - which they routinely use or will use in the near future to study cosmic objects of interest. 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.

Radio Astronomy:

Recent radio astronomy research at RRI has been on using the MWA telescope to study the phenomenon of sub pulse drifting which may hold the key to understanding the pulsar emission mechanism. Pulsars are rotating neutron stars or white dwarfs that emit a beam of radiation; the rotation results in the appearance of pulsed emission and hence the name. Another work has used the MWA along with other telescopes to estimate, for the first time and over the frequency range 80-1400 MHz, spectra from radio haloes and relics (enormous regions of diffuse radio emissions) in merging galaxy clusters. Use of a high resolution GMRT HI mapping has allowed RRI astronomers to resolve and study in great detail smaller scale features in a system of two interacting spiral galaxies, spiral debris and a tidal dwarf galaxy. This has enabled RRI astronomers to estimate their dynamics and propose formation mechanisms for the tidal dwarf galaxy. RRI astronomers have used in-house built spectral radiometers SARAS 2 to derive likelihoods for plausible redshifted 21 cm signals from neutral hydrogen, which is a key probe of "Cosmic Dawn" and the "Epoch of Reionization". Comprised of super-massive black holes at the centers of massive elliptical galaxies powering twin-jets of synchrotron plasma, radio galaxies are manifested in a variety of morphologies arising from the deposited plasma radiating predominantly at radio frequencies. Research at RRI in this area in recent years has focused on eliciting information on central black hole behaviour from the radio emission imaged on much larger scales.

X-ray Astronomy:

By studying the X-ray mid-eclipse (time when the X-ray emitting compact star is exactly behind the companion star)



Clockwise from top left:

MWA radio telescope as a precursor to the International Square kilometer array (SKA) telescope, Building Radio astronomy Detectors for discovering first formation of atoms, stars and galaxies in the universe, SWAN – Sky Watch Array Network, Developing X-ray Polarimeter (POLIX) as payload for ISRO's XPoSat, to be the world's first X-ray polarisation Mission!

and timing record of an X-ray binary (a two star system where one of the stars is a neutron star or a black hole) researchers at RRI have discovered the presence of a massive planet (approximately 8000 times the mass of Earth) around the binary. Careful analysis of variations in X-ray intensity and spectral parameters as a function of orbital period has enabled astronomers at RRI to propose a scenario, which explains the nature of the most highly absorbed X-ray binary in our Milky Way galaxy. Astronomers at RRI have measured changes in the pulse phase dependence of X-ray emission lines with a torque reversal in a unique X-ray binary 4U 1626-67, which indicates that the structures in the accretion disk that produce pulse phase dependence of emission features have changed from spin-down to spin-up phase.

Design, construction and operation of telescopes

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. Additionally, new methods and modeling 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. Efforts are 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. RRI is currently designing and building an Indian X-ray polarimeter (called POLIX), as a payload for a dedicated small satellite mission of ISRO called XPoSat. POLIX is poised to be the first dedicated X-ray polarimeter mission in the world and open a new window in high energy astrophysics by measuring X-ray polarization in about 50 bright X-ray sources, ahead of the NASA and ESA space mission proposals for launching X-ray polarimeters. Research in signal processing has been geared towards developing error correcting codes, methods to search/detect unpulsed emissions intrinsic to pulsars, new approaches with low data processing requirements for detecting pulses that undergo dispersion and foreground modeling and subtraction for long wavelength astronomy.

Light and Matter Physics (LAMP)

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 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. For example, understanding the fundamental quantum aspects of light will enable super-secure communication and information transfer.

Focus 2016- 2017

Ultra-cold-atoms, ions 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 cold collisions and interactions at low temperatures. An ultra-cold and dilute gas of di-atomic molecules of ^{85}Rb atoms, which are cooled to just above zero Kelvin kinetic temperatures are formed using laser light induced photo-association. These are then ionized to form $^{85}Rb_2^+$ ions, which are then trapped. These trapped ions are used to study their decay rate by photo-association. The analysis of the experiment and its theoretical interpretation allows extension of this understanding to more complex systems.

An experimental study, which overthrows a long held view that heavier atoms cannot cool lighter trapped ions, was undertaken in the past year with successful results. It was experimentally demonstrated that cooling of trapped lighter ions is possible by collisions with co-trapped, higher mass neutral atoms. Separately, scattering measurements from cold atoms trapped in a low-volume trap indicated the role of statistics in determining the unique transition signature when laser light interacts with atoms and gets converted to a light of different nature. A new experimental facility towards creating a Sodium-Potassium gas mixture at nano-Kelvin temperature was started in the LAMP group during the year. At these very low temperatures the system can be an ideal test bed for investigating quantum nature of interactions between these mixtures. Such a study will throw light on critical physical principles underlying complex condensed matter systems like those which show superconductivity.

Cavity Quantum Electrodynamics

Atoms interacting strongly with a single-mode of an EM field inside a high-Q cavity is a touchstone experiment for realizing quantum features of interaction between the atom and the cavity mode. In the past year two different experiments were performed to bring out the nonlinear nature of atom-cavity-field interaction. In the first experiment significant progress was made in measuring interactions between trapped ions and cold atoms, using changes on cavity coupling of the atoms when interacting with ions. The measurement is non- destructive and therefore has important

consequences for in-situ measurements with cavities.
In another experiment, a rapid high contrast optical switching was achieved by making thermal atoms interact with both optical and microwave photons. It was shown that by changing the phase of the microwave photon trapped inside a microwave cavity a high contrast intensity switch in the optical domain is achieved.

Interaction of intense laser fields with solid targets

The optical response of a material scales linearly with respect to incident radiation. However, when the intensity of the incoming radiation (in other words the amplitude of the electric field) is sufficiently high the material can respond nonlinearly. The study of 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 a 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. A variety of materials were studied using short and ultrashort laser pulses, with the aim of investigating the nonlinear optical absorption properties in the nanosecond and femtosecond regime. In another work, laser ablation was used to optimize the surface structure of Si for enhanced ion and electron emission. Plasmas can be generated in the lab by the interaction of intense laser pulses with suitable targets. Such laser-produced plasmas have myriad applications, such as nanoparticle and nanocluster generation, second and high-order harmonic generation, UV and EUV generation, X-ray generation, and attosecond pulse generation. Research over the past year at the Institute was towards understanding the emission dynamics and properties of plasmas generated from Al, Cu and Zn targets.

Mitigating classical noise effects and understanding and controlling quantum noise

The property of quantum entanglement, which endows super powers to a quantum system, is susceptible to degradation owing to exposure and interaction with its environment. A practical scheme involving a simple NOT operation is proposed which will delay and sometimes completely cancel the degradation on the entangled systems.

Understanding the critical features of noise in combined atom-light systems is essential to protect the system from decoherence. Measurements of spin fluctuations in a thermal vapor was performed using a far detuned probe laser passing through a thermal vapor in presence of an orthogonal magnetic field studying the spin-noise induced Faraday rotation.

Theoretical studies on noise effects on quantum properties of optics-atom-microwave interaction was also undertaken during this period to understand how transfer of quantum-noise properties occur over very different frequency domains.

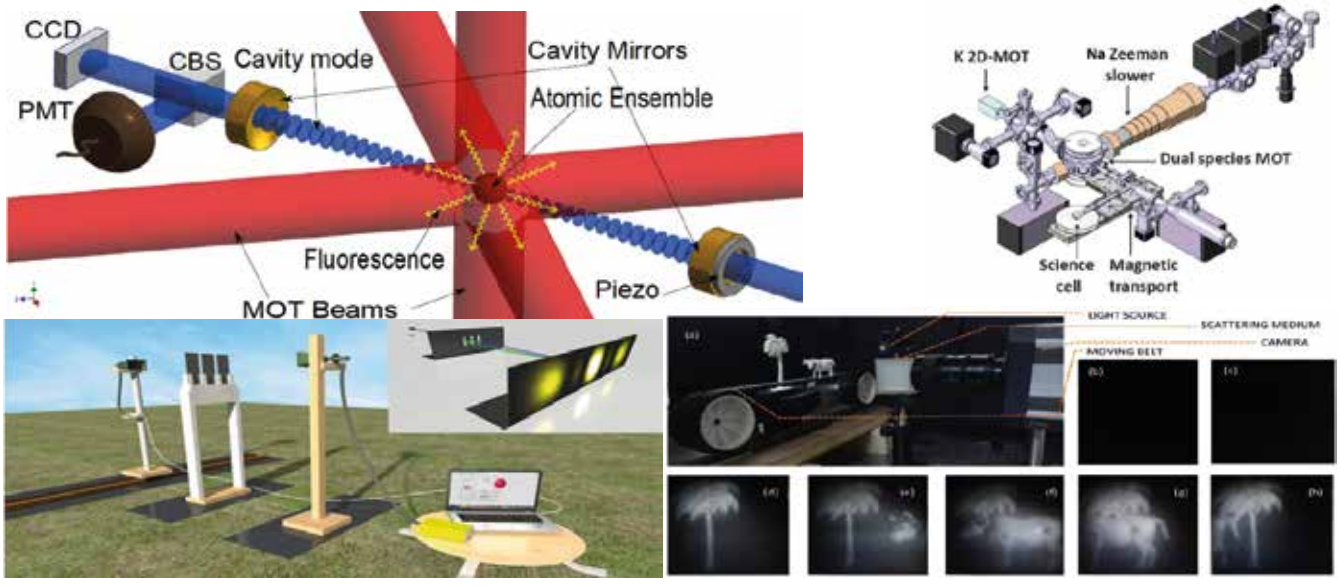
Classical noise can have very immediate and detrimental effects. To cite an example let us consider the very real situation of an aircraft trying to land in foggy conditions. Visibility is diminished due to random scattering of runway light by water droplets in air introducing lot of noise in imaging the runway lights. To mitigate this effect, a scheme was envisaged and demonstrated in a tabletop experiment where clear images were obtained in real time through strongly scattering media equivalent to a quarter kilometer of moderate fog.

Quantum computation and tests on fundamental principles of quantum mechanics

During the past few years RRI has accumulated infrastructural capability and intellectual knowhow to conduct cutting edge research in the fields of quantum information, quantum computing and quantum communication using quantum optics based tools. It is worth pointing out that the Institute has pioneered the manufacture and applications of single, heralded and entangled photon sources in India which were hitherto unexplored in our country. Research during the past year was focused on the following:

A spin-half system consisting of up and down spin states is a proto-type qubit system on which computational states of 1 and 0 can be mapped for quantum computational purposes. As is well known a base-2 quantum computer operating with n such two-state entities will have 2^n possible states available for quantum computation. If there is base-3 system then the advantage is 3^n!. An experiment producing such a pair of qutrit states was performed and their spatial correlations were mapped during the year.

The naive application of the super-position principle in experimental and theoretical studies involving multiple slits interference experiment was questioned. It was brought out both experimentally and theoretically that boundary conditions have a very non-trivial effect on the so-called Sorkin parameter. The experiment, which was done with microwaves, showed that indeed even without violating fundamental principles of quantum mechanics the Sorkin parameter could be non-zero due to in-correct application of boundary conditions.



The experimental setup to measure interactions between ions, atoms, molecules and light, in any combination of these. All these species can be trapped and controlled in the experiment, so that they overlap and interactions between them can be measured with precision in a controlled manner. Schematic of the experimental setup for creating Quantum mixtures, Schematic of experimental setup for measuring the deviation from the superposition principle in interference experiments, Successful real time imaging through turbid media.

Soft Condensed Matter (SCM)

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 2016-17

Aging and soft glassy rheology

Naturally occurring soil is a mixture in which fine sand, colloidal clay and salt (minerals) are the major components. The structure of soil and hence its behavior is heavily dependent on the relative concentrations of the constituents.

For example soil acidity is known to be a limiting factor in plant growth thus playing a direct role in dictating agricultural yield and economy of a country. On the other hand salinity of soil can explain various geophysical phenomena such as landslides and river delta formation. Thus, from a practical viewpoint, a fundamental understanding of the effect of relative concentrations of salt and acid on the structure-property relationship of soil is highly desired as this could pave the way towards increasing crop yield as well as disaster management. Surprisingly, a comprehensive study that could shed light on the structure and properties of colloidal clay as a function of salt and acid concentrations is distinctly lacking.

Researchers from the SCM group at RRI have addressed this with a set of experiments in which they monitored the stability of suspensions of acid and salt induced clay in water. The results obtained indicate that acid induced clay is stronger than salt induced ones. The yield stress, which is the stress (force applied within a region) at which the clay suspension gives way under applied shear force, increases with salt initially before reaching a critical limit after which it begins to decrease with increasing concentrations of salt. A non-monotonic evolution of yield stress (which is the stress-force applied within a region-at which the clay suspension gives way under applied shear force) with idle time (time since preparation of clay) is observed in acid induced clay but no such time dependent behavior is found for salt induced clay. The observations are explained in terms of the osmotic pressure induced aging

behavior of the sample and are verified using Cryo-SEM and UV–Vis spectroscopy experiments.

Understanding the emergence of solidity (fluid to solid transitions) in soft materials is another important area of research since we encounter this behavior in our day to day life-some examples being shaving foam, paint and toothpaste. Depending on the particle size there are two ways such transitions can occur (i) by a reduction in the temperature of the system (glass transition), (ii) by increasing the density of particles (jamming transition) and (iii) by removing shear from the system. Owing to the myriad practical applications of such systems detailed studies on these transitions are highly desired. Experiments were performed at RRI to understand the role of fragility (a measure of rate of change in system relaxation time with temperature or particle density) as a function of polydispersity in suspensions of soft colloidal particles approaching the jamming transitions. They find that fragility and intrinsic nonlinearity increases with polydispersity and attribute it to the prevalence of dynamic heterogeneities in these polydisperse systems. These results clearly demonstrate that jammed suspensions of colloidal particles can be effectively fluidized (solid to fluid transition) with increase in polydispersity of particles. These results could have potential applications in systems requiring solid to fluid transitions.

Liquid Crystals (LC's)

As the name implies, a Liquid Crystal 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. LC's may 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, which are amphiphilic materials composed of a polar head group and non-polar chain, in a solvent.

Thermotropic LC's 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.

LC's 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 holds the key for 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 study of various interesting physical properties resulting from an intelligent tuning of the molecular shape, concentration, constituents and phase expand the LC knowledge base and thereby serve to open avenues for technological applications.

Bent core LCs – Design, synthesis and structure-property relationships:

An interesting subset of LC's are the so-called Bent-Core (BC) LCs, which are composed of molecules with a bent aromatic core and which self organize themselves in unique ways. Exploiting the unique polarity (due to the bent shape of the molecules, free rotation along their long axes is hindered and dipole moments are ordered to develop a polarity) and chirality properties of BC LCs has necessitated developing new central bent-core units followed by a detailed understanding of their structure-property relationship. The LC group at RRI has discovered that ethylenedioxythiophene (EDOT) can be used as a central unit for the synthesis of bent-core LCs. In a related study, EDOT was encompassed with a Schiff base. Upon investigation, it was found that the phase behavior was influenced by the interplay between temperature and the number of repeating units that make the central bent-core unit.

The origin of ferroelectric switching behavior in bent-core liquid crystals is a highly debated topic. The formation of polar nematic phases as well as the formation of smectic C-like cybotactic clusters have been proposed as possible mechanisms to explain this behavior. Research in the past year, using electro optic and dielectric studies on a homologous series of four ring BC LCs, had suggested the formation of such smectic C cybotactic clusters in the nematic phase. Detailed XRD measurements have now been carried out in RRI, which corroborate these observations.

Earlier work by the LC group on novel smectic phase exhibited by BC hockey stick (BCHS) molecules was extended this year to include a new series of BCHS molecules. Apart from confirming earlier results, they also found new phases and correlate the chain length of the central unit to the stability of these phases. Interestingly, these phases exhibit remarkable electro-optic response making them potential candidates in optoelectronic applications.

Phase separation is a phenomena observed in a wide variety of fluids. In complex fluids composed of fast and slow components, viscoelastic effects are known to influence phase separation and pattern formation. The effects of viscoelastic

phase separation can be more dramatic when the components exhibit LC phases. Research staff from the LC group at RRI has shown evidence of such effect in some binary mixtures composed of LCs made of rod-like and bent-core molecules. The differences in size and shape of the constituent R and BC molecules and thereby the flow and rotational viscosities of the molecules causes the formation of cellular structures. This type of phase separation process has the potential to provide a possible technique of forming functional ordered assemblies of nanoparticles embedded in a liquid crystalline matrix.

Liquid crystal Nanoscience:

Research efforts at RRI have 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, storage and photovoltaics. A new series of liquid crystals decorated with gold nanoparticles have been synthesized, with attractive photoisomeration behavior, which could be exploited for applications in the field of molecular switches and optical storage devices. These hybrid platforms also display orders of magnitude increase in electrical conductivity as well as increase in non-linear absorption. It was also observed that a Discotic LC (DLC) gold nanoparticle hybrid decreases the phase transition temperature of the LC while increasing the ionic conductivity. Azobenzene based gold nanoparticles have shown longer photoswitching duration due to the steric hindrance developed by multiple attachments of azobenzene molecules to the central gold nanoparticle core.

A comprehensive research report of DLC dispersed with metal, semiconductor and carbon nanoparticle hybrid platform was made by research staff in the LC group at RRI and has crystallized in the form of a major review article published in the Journal of Physics. The review discusses the synthesis and characterization of various combinations of DLC and nanoparticles that led to enhanced performance without affecting the supramolecular properties.

Liquid Crystal-photovoltaics:

Another important area of research, given the overdependence on fossil fuels and their contribution to global climate change, is alternate energy sources. The main player, in the Indian context, given that the countryside is bathed in abundant sunshine, has to be solar energy. RRI is working on developing liquid crystals for photovoltaic applications. Two designs in which bulk heterojunction solar cells were incorporated with liquid crystalline triphenylene derivative as well as carbazole copolymer and fullerene derivative with an inserted layer of discotic material showed higher efficiency. Additionally, the effect of varying the thickness of the LC layer and annealing on the output characteristics of these devices were also studied.

An overview of developments in the field of organic photovoltaics, with liquid crystals incorporated into different types of solar cells, including their corresponding efficiencies and future outlooks in the field of self-organizing supramolecular LC photovoltaic research, appeared as a report in Polymer Journal - a journal that is part of the Nature Publishing Group.

A review of discotic LCs derived from aromatic cores including grapheme, with focus on recent developments and future outlook on organic semiconductor materials and applications, has appeared as a review in the journal Liquid Crystals – a premier journal within the LC community.

Liquid crystals – phenomenological theory

Theoretical investigations in the SCM group primarily focus on the theory of elasticity and topological defects in soft matter. Orientation (such as nematic, vector, hexatic) tangent-plane order on two-dimensional membranes deformable in three dimensions suffers frustration on curved membranes. This is also the case for certain smectic liquid crystals, and thin crystalline lamellae. For example, solution- and melt grown polymer crystallites grow in the form of lamellae, exhibiting diverse morphologies such as helicoidal-, tent- and scroll - structures. Attempts are being made to formulate a phenomenological theory based upon the interplay between elasticity and topological defects to explain the stability of observed morphologies.

Biophysics 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). The diameter of the axon is only about a micron and in normal cells it is almost constant for the entire length. This robustness may be because the diameter is set by a balancing act between two opposing physical factors, example, the axonal membrane tension that tries to reduce the diameter is balanced by the entropic internal pressure due to the polymer gel that fills the interior (cytoskeleton). Moreover, maintenance of axonal plasticity requires that the neuronal cell should be able to retract and reform connections. Researchers at the biophysics group at RRI are trying to understand the reasons and the mechanisms behind axonal plasticity. They hypothesize that molecular motors and polymer dynamics are at work as they can generate stresses and flows to actively remodel the cytoskeletal structure. Specifically they are attempting to answer the following questions: How do axons maintain a

constant diameter over such long lengths? What determines the generation and redistribution of components during axonal growth? What drives the retraction of axons during axonal rewiring?

Additionally, the group at RRI also investigates active axonal membrane dynamics and mechanics using a home-built optical tweezer. The approach includes development of simple assays, image analysis techniques and fluorescence microscopy methods, and use of genetic and biochemical tools. As no readymade off-the-shelf equipment are available for some of these quantitative biophysics experiments, a significant part of the work is on the development of new tools. Some recent examples of such capability building are: a new type of force apparatus that can measure with pico-Newton and nano-meter precisions, a compact device to apply rotational fluid shear stress to cells in order to quantify cell adhesion properties.

Using the force measuring apparatus invented and built in-house, the RRI biophysics team has explored the viscoelastic response of live axons to applied strain. Contrary to the strain hardening response seen in other cell types they observe a strain softening response, which they attribute to the force-induced unfolding of spectrin molecules that interconnect actin (proteins essential for cell motility and contraction) structures in axon.

Another area of research has been on understanding the dynamics (growth, contractibility and retraction) of filipodia by using membrane tethers pulled out of axons of neuronal cells as model systems. Results point towards the twisting of actin filaments by actin binding proteins as responsible for the contractile response of filipodia. These processes play an important role in axonal path finding (directional movement).

Again, using the in-house shear device mentioned above, the biophysics group have quantified, with the aid of mathematical modeling, cell adhesion by measuring the cell detachment under a constant shear as a function of time and shear stress.

In an effort to understand the shape stability of axons, actin filaments were depolymerized and the resulting shape evolution was studied. Peristaltic radius modulation (beading) was observed and by tracking the transport of a fluorescent probe it was shown at RRI during the year that transport in axons was not the cause of beading as previously thought. Instead, laser ablation experiments at the Institute show that these shape changes may be caused by breakages in the cytoskeleton. Experiments are ongoing to verify these observations.

Nanoscale Biophysics of Biological Systems

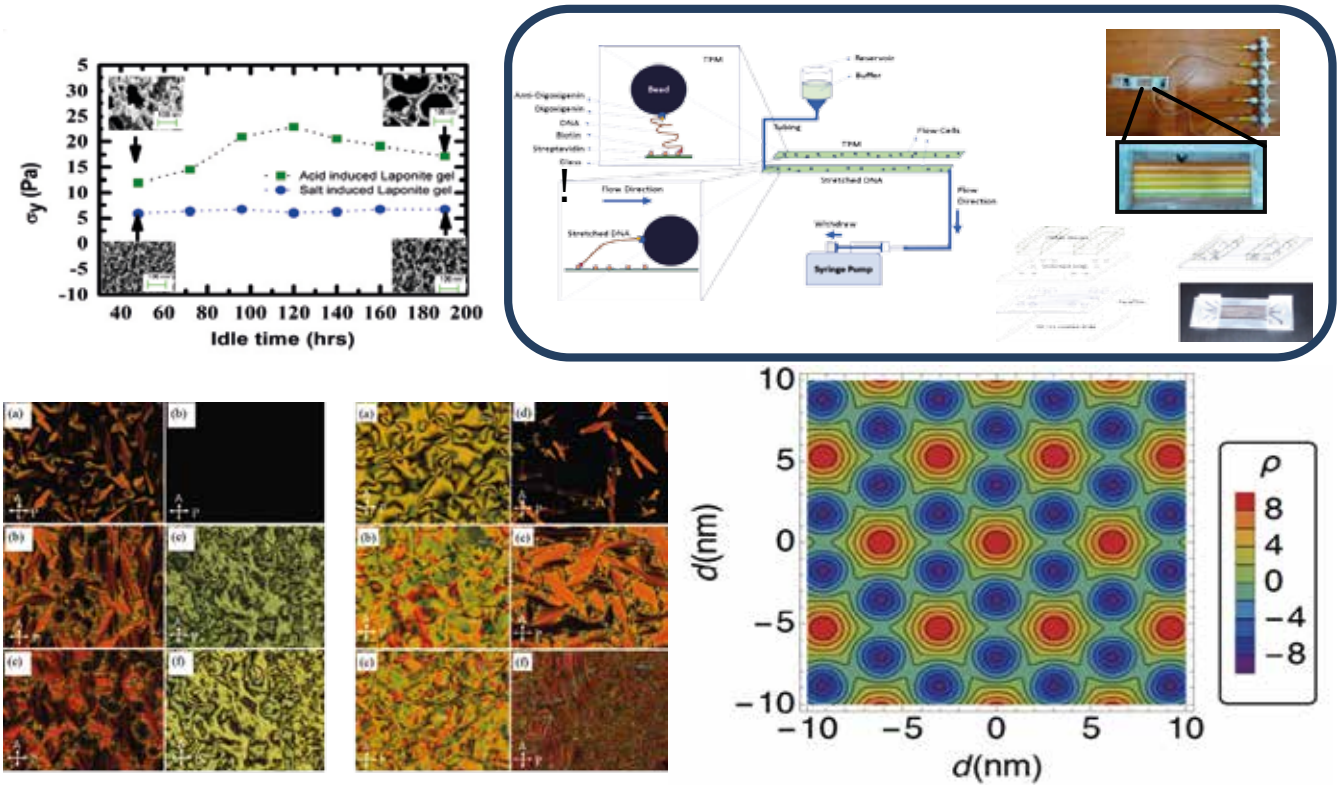
Understanding of physical mechanisms of biological structures and machines, at the molecular and cellular scale, is paramount to understand development and disease. Nanoscale biophysics is primarily guided by the intriguing synergy of structures in biological systems and their functional dynamics. Researchers use, as well as develop, novel nano-technological tools to decipher biophysical principles governing role of forces in cellular as well as molecular assemblies. They try to understand the cellular mechanisms in sensing of forces as well as response of cells/molecules in model systems of self-assembly of proteins, DNA-protein complexes as well as whole cell stiffness.

Specific interest lies in chromatin structure-function relationships from a biophysical point of view. Changes in chromatin structure are a key element in epigenetic gene control. Activation and/or transcriptional-silencing of genes via condensation-decondensation of chromatin are its ubiquitous features. Defects in how chromatin is locally condensed are relevant to physiological and pathological processes. However, the molecular mechanisms that establish and maintain functionally distinct chromatin compaction states are poorly understood.

In the RRI biophysics laboratory, the focus is on measuring the structural interactions that underlie molecular function in biological systems using a plethora of single molecule nanoscience tools. The nanoscale biophysics group at RRI has developed in-house a microfluidics platform wherein the extension of DNA tethered on glass side and connected to a microbead on the other end is studied as a function of flow rate. Such force-extension measurements have broad applications in biophysics and soft condensed matter research. They have also measured the molecular volume of CENP-A nucleosomes, which has paved the way to resolve longstanding questions in the field of nucleosome architecture during chromosome segregation in the process of cell division.

Physics of lipid membranes and polyelectrolytes

Sterols such as cholesterol are essential components of many biological membranes and play an important role in various cellular functions. Over the years, researchers at RRI have been studying the effect of these molecules on model lipid membranes, consisting of a few components. These studies have led to a better understanding of the influence of sterols on the structure and phase behavior of lipid membranes. Recently, studies on the interaction of mononucleotides with lipid membranes have been initiated, motivated by the RNA hypothesis of the origin of life on Earth, whose hypothesis is that these interactions led to the formation of the first self-replicating molecules.



Clockwise from top left:

The yield stress of acid induced clay gels varies monotonically with sample idle time because of the evolution of the microstructure of the samples (see Cryo-SEM images in the top insets). No such change in yield stress is observed in salt-induced clay gels as the sample microstructure does not change appreciably with idle time (see Cryo-SEM images in the bottom insets).Fabrication of a Microfluidics chip to measure effect of fluid-flow force on single DNA molecules. This microfluidic chip is mounted on a customized microscope to record the real-time thermal fluctuation of a molecule to study its statistical physics properties. (A) Shows the experimental schematic; (B) shows the setup. The inset shows 5 parallel microchannels fabricated next to each other for higher experimental throughput. Here the channels are filled with contrasting coloured fluids for better visualization. (C) The fabrication process.

POM optical texture for compound A9 under cross polarization for planar aligned sample: (a) SmA phase with coexistence of isotropic phase at 124.7 C, (b) uniform focal conic fan texture in SmCM phase at 122 C, and (C) broken focal conic fan texture SmC S phase at 114 C. For the homeotropic aligned sample: (d) dark homeotropic texture in SmA phase, (e) schlieren texture dressed up with undulations in SmCM phase at 122 C, and (f) clear schlieren texture in SmCS phase at 114 C.

POM optical textures under cross polariser of compound A14 for homeotropic alignment: (a) schlieren texture just below clear temperature, (b) birefringent schlieren texture in SmCAZA phase, (c) birefringent schlieren texture with domains in SmCIZI phase. For planar: (d) SmCA ZA phase just below clear temperature, (e) fully grown focal conic fan texture in SmCAZA phase at 118 C, and (f) irregular band structure in SmCI ZI phase.

Electron density map of a hexagonal phase formed by a surfactant-DNA complex

Polyelectrolytes are polymers carrying ionizable groups. They are ubiquitous in biological systems. Biopolymers such as DNA, RNA and proteins are examples of polyelectrolytes. Polyelectrolytes of opposite charges form insoluble complexes, called coacervates, in aqueous solutions. Coacervates are interesting from a fundamental point of view as well as due to their potential applications. Researchers at RRI have been studying structures of coacervates made up of semi-rigid polyelectrolytes. These system exhibit interesting structural polymorphism and efforts are underway to understand the thermodynamic stability of the different structures.

Theoretical Physics (TP)

Theoretical physics is an endeavor that attempts to make sense of the inner workings of nature, using the language of mathematics. The goal is to model and predict the behavior 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 group at RRI is actively pursuing research in the following areas: Foundations of quantum mechanics, General Relativity, Quantum gravity and Statistical physics. 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 nonlinear quantum optics. The overlap with the Soft condensed matter group is in areas such as biophysics, polymer physics and modeling stochastic search process. Additionally RRI theorists have fruitful ongoing collaborations in the above research areas with both national and international peers.

Focus 2016-17

General Relativity and Quantum gravity

Gravity, as we all know is a force that attracts a body towards the center of the earth. With Newton's work it became possible to understand gravitational effects with a few simple laws. However, a deeper understanding of gravity only emerged in 1915 with Einstein's theory. The theory of General Relativity explains that the force we perceive as gravity results from the curvature of spacetime (a 4 dimensional entity -3 dimensional space and one dimensional time). An oft-quoted analogy to visualize the curvature of spacetime in the presence of a celestial body is the stretching of a taut rubber sheet around a heavy sphere placed on it. Placing a smaller sphere on this curved region and imparting it with just the right momentum will cause it to revolve around the bigger sphere. The smaller sphere experiences a gravitational pull towards the heavier sphere as a result of the curvature of the rubber sheet. On the other hand we have the standard model which explains basically everything else in terms of the three forces-electromagnetic (the force that governs the attraction and repulsion of charged particles like electrons), the strong force (the force that keeps the nucleus from falling apart) and the weak force (responsible for radioactive decay). The Standard model and General Relativity are two theories that explain the known world. Unfortunately, owing to their incompatibility, merging the two theories is a very difficult task. In fact, the Holy Grail for many physicists is to merge these two theories into a Theory Of Everything. The incompatibility can be traced to the origin of the fundamental forces. In the standard model systems interact via quantum particles or force carriers and evolve within a background spacetime structure whereas in General Relativity curvature of spacetime is the origin of gravity. The fabric of spacetime acts both as the background structure for gravitational interactions as well as a dynamic phenomenon, giving rise to this interaction.

Loop Quantum Gravity (LQG) overcomes this incompatibility by generalizing 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.

Another approach to overcome the incompatibility is Causal Set Theory (CST). CST is built on two basic postulates, that (i) spacetime is discrete, made of indivisible units or quanta, and that (ii) Causal structure contains geometric information: knowledge of events that are causally connected to other events. The combination of the above two leads to the idea of a causal set as a fundamental structure of spacetime. In the past year researchers at RRI have furthered our knowledgebase in both the above avenues of research in quantum gravity.

RRI researchers in collaboration with international peers have shown echoes of asymptotic silence in causal set quantum gravity. Asymptotic silence is a state of space in which information between two space points cannot be exchanged or in physics terminology the space points decouple. By making use of an intrinsic definition of spatial distance between causal set elements, they show that the spatial distance is always greater than the continuum proper distance between elements. Moreover, because of fluctuations arising from randomness the difference in spatial distance and proper distance is larger in smaller length scales. They interpret this as a manifestation of asymptotic silence.

Previous research at RRI on the large N limit in 2D causal set quantum gravity showed a phase transition from a continuum phase to a crystalline non-continuum phase that affects the Hartle - Hawking ground state (Hartle - Hawking ground state is the ground state for the Hartle - Hawking wave function for CST). During the past year, researchers at RRI have deduced that for a finite temperature, the continuum phase corresponds to anti de Sitter space.

Current proposals for quantum dynamics in LQG do not seem to encode propagations between macroscopically separated regions of quantum geometry because the relevant Hamiltonian operator acts ultra-locally. Such propagation is desired so as to possess a relevant classical limit in LQG. Research at RRI over the past year within the framework of LQG type quantization of 2D field theoretic toy model has yielded robust structural lessons for putative constructions of this operator in LQG. Currently efforts are towards extending the work from the simpler toy model to a weak coupling limit of Euclidean gravity.

In a path integral approach to quantum gravity, one has to divide up spacetime into pieces and focus on the action within

each piece. A desirable property of the action is that it should be additive when we glue the pieces back together. This is achieved only when one properly takes into account the boundaries of the pieces. The boundaries can be spacelike, timelike or null. Much work has focused on the first two cases. The Einstein–Hilbert Action principle for spacetime regions

with null boundaries has only recently attracted attention. Researchers at RRI have provided a unified approach to all the boundary signatures using both the computationally simpler Cartan's tetrad formalism as well as the more familiar metric formalism.

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.

Research during the past year on the nature of correlations between particle velocities in driven dissipative systems has shown that the correlation function decays exponentially with distance. In a related work, they show that in a driven inelastic one-component Maxwell gas the steady state velocity distribution is strongly influenced by the nature of driving and at the asymptotic limit behaves like a non-interacting Maxwell gas.

Recent research at RRI has advanced our knowledge base by extending the problem of random walk for modeling stochastic search process to include arbitrary N independent random walkers. They calculate the probability density function (PDF) of the minimum time needed for a random walk to visit all sites within a domain, and show that for a given boundary condition the PDF depends explicitly on the number of random walkers. This study contributes to a better understanding of stochastic search process in nature such as animals foraging for food, various biochemical reactions etc.

Quantum Diffusion

A dust particle suspended in a fluid will undergo random motion (diffusion) as a result of collisions with a number of atoms or molecules that make up the fluid, whose motion in turn is due to thermal fluctuations. Thermal fluctuations are nothing but the jiggling and wiggling of atoms and molecules, which manifests as temperature of the fluid. Lower the jiggling and wiggling less is the temperature and vice versa. What happens when we lower the temperature of the system and scale down the size of the particle until we reach a regime where thermal fluctuations are negligibly small and the diffusion is driven primarily by zero point fluctuations, purely of quantum origin?

Researchers at RRI analyzed diffusion at ultra low temperatures and derived a response function that led to a logarithmic diffusion law in the quantum domain. Further they proposed experiments that could be realized with existing technology using cold atoms.

Using the concepts of Argand diagram and Burgers circuit, researchers at RRI demonstrated the possibility of partial density states in mesoscopic systems. Further, they showed that possibilities exist for a general connection between phase drops and exactness of semi-classical Friedel sum rule.

Nonlinear Quantum Optics

The optical response of a material scales linearly to the electric field of incident radiation. However, when the intensity of the incoming radiation (in other words the amplitude of the electric field) is sufficiently high, the material could respond nonlinearly. The study of the interaction of intense light with matter is subject of nonlinear optics. Nonlinear quantum optics is a relatively new field to specifically investigate nonlinear light-matter interaction in the quantum regime with few photons.

An optical isolator creates nonreciprocal transmission (difference in light transmission upon reversal of incoming light direction) and is an important component in optical circuits. Currently, these devices are made of magneto-optic materials making on-chip integration troublesome. To overcome this difficulty, RRI researchers have proposed a nonlinear optical isolator that performs via optical nonlinearity and spatially asymmetric linear permittivity. They examine the physical mechanism and properties of nonreciprocity by calculating the transmission of light in model systems and propose ways to improve nonreciprocity.

Using quantum Langevin equations and Greens function, researchers at RRI have developed an exact method to investigate transmission and reflection of a laser through optically nonlinear quantum media of atoms. Additionally, they derive correlation properties of atoms driven by the laser field.

Polymer Physics

A polymer is a large molecule that consists of repeating subunits and can be thought of as a chain of identical molecules connected end to end. If the repeating subunit is a biological entity then it is a biological polymer. These polymers exist as linear chains or they can loop around to form rings. Loop formation plays a crucial biological function in many biological semi-flexible polymers. For example, in a DNA (Deoxyribonucleic acid, the storehouse of genetic biological information) molecule, distant parts of the molecule need to come together to form a loop for certain

gene regulation processes to get initiated. More recently, there have been experiments studying loop formation in the biopolymer actin. Actin plays a critical role in many cellular functions including cell mobility, shape and muscle contraction. In general, bending (for example leading to loop formation) and torsional (leading to twisting) properties of biological polymers can directly influence numerous cellular processes. For all these reasons, it is important to study the mechanical properties of biological polymers by performing theoretical analysis followed by experimental verification.

RRI theorists, with collaborators, have performed theoretical calculations that predict the probability of loop formation in semi flexible polymers. They use the pure bend Worm Like Chain (WLC) model, which is the standard model commonly used for understanding the elastic properties of biopolymers. This model considers the polymer chain to be a continuously flexible rod, something akin to rod-shaped putty, which can be twisted and bent as desired. The loop formation probability predicted from this study can be tested against fluorescent actin cyclization (loop forming) experiments. They also discuss the effect of ring closure on bend-angle fluctuations in actin polymers. The bend-angle fluctuations predicted by theory can also be tested against laboratory experiments.

Closing remarks

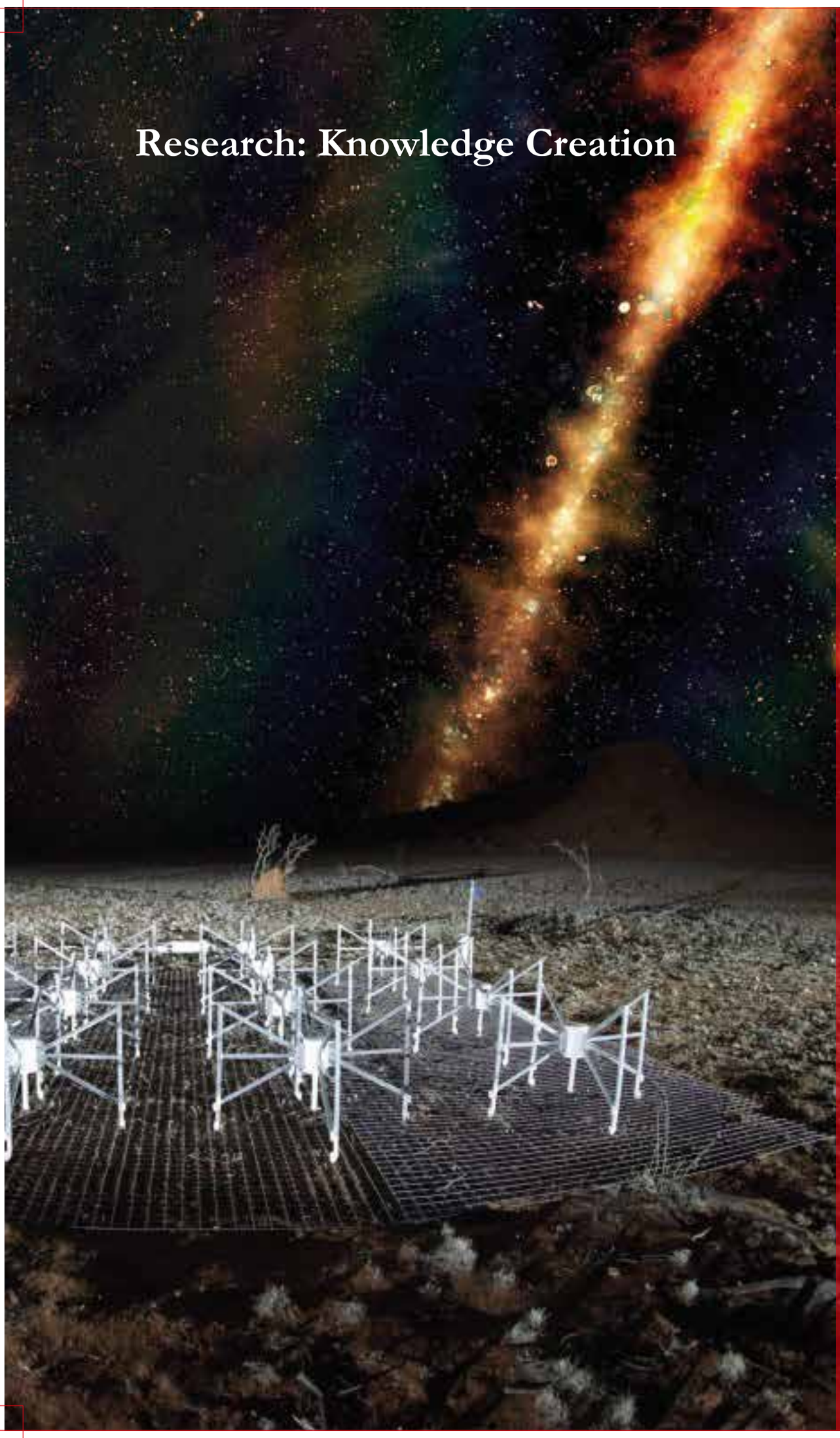
Since the days of our Founder, Sir C V Raman, the Institute has engaged in experimental research of a kind that is becoming uncommon. We selectively target a few unsolved questions in basic science that require purposeful innovation – a building of apparatus in Astronomy, Quantum atom optics and information, 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 our 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., real time imaging through fog involving a novel low-cost method that uses an algorithm that could be executed using the parellisation capabilities of common desktop computers, with obvious applications in defense, search and rescue and medical imaging to name a few, 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 leverages on our long standing expertize in liquid crystals to develop organic photovoltaics.

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 close to 200 students, 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 by dissemination of knowledge by 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. It is worth noting that DST has shared many of our posts through their official facebook account.

Research: Knowledge Creation



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) The third aspect involves the design, construction and operation of telescopes, which are often built for very specific purposes, and are strategically located around the world and in space.

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

Focus 2016-17

Theoretical Astrophysics

One could not be faulted for staring at the starry sky and coming to the conclusion that we live in a more or less static universe and nothing interesting is going on "up there". However, nothing could be farther from the truth. The Universe is actually a very vibrant place where various dynamic processes occur on all length scales from stars to galaxies to galaxy clusters and beyond that shape their evolution. Stars are born, evolve, eject gases into the atmosphere (stellar winds), and eventually some of them end their lives in spectacular explosions called supernovae. A combination of stellar winds, black hole jets and or shock waves from supernova explosions result in a shell of interstellar gas known as bubbles and super-bubbles. Galaxies in clusters merge with other galaxies, some display a very high rate of star formation (starbursts) and most harbor supermassive black holes at their centers. Detailed theoretical studies shed light on these processes and add to the knowledge base of our understanding of the Universe. The sections below are structured as follows – a brief introduction to each of these topics is provided followed by detailed description of the research that falls under that topic undertaken in 2016-17.

Intracluster medium

Intracluster medium at large cluster radii

Theoretical Astrophysicists at the RRI in collaboration with international peers analyzed the data from a sample of galaxy clusters (Sunayaev-Zeldovich (SZ) effect and X-ray surface brightness data), in order to study the physical state of the intracluster gas at the outer regions. These regions are least affected by radiative cooling as well as AGN feedback from the central region. Therefore, the entropy of the gas in this region holds clues to the evolution of the intracluster gas. The results of the study showed, for the first time, that the excess entropy in this region is close to zero, and therefore rules out models of 'preheating' in which the intracluster gas is thought to be heated before falling into the cluster potential.

[Asif Iqbal, Subhabrata Majumdar, Biman B. Nath, Stefano Ettori, Dominique Eckert and Manzoor A. Malik]

Galactic outflows

Effect of Radiation in superbubbles

In an earlier work, researchers at the Institute had touched upon the possible effects of radiation pressure in the expansion of a bubble around young stars. During the past year, with analytical calculations and 1-D numerical hydrodynamic simulations, these effects were worked out in greater detail. It was found that radiation pressure is indeed important for the first million years or so, after the onset of star formation in a cluster, after which heating due to radiation becomes important.

Energetic winds and radiation from massive star clusters push the surrounding gas and blow superbubbles in the interstellar medium (ISM). Recent research at RRI was geared towards understanding the role of radiation in the dynamics of superbubbles driven by a young star cluster. For a realistic time evolution of the mechanical power as well as radiation power of a young star cluster of mass 10^6 $M_\odot$, and detailed heating and cooling processes the ratio of the radiation pressure on the shell (shocked ISM) to the thermal pressure ($\sim 10^7$ K) of the shocked-wind region is almost independent of the ambient density, and greater than unity before $\lesssim$1 Myr. The size of the hot gas ($\sim 10^7$ K) cavity was found to be independent to the dust opacity [$\sigma_d \approx (0.1–1.5) \times 10^{-21}$ cm^2], whereas the structure of the photoionized ($\sim 10^4$ K) gas depended on it. Most of the radiative losses occured at $\sim 10^4$ K, with sub-dominant losses at $\lesssim 10^3$ K and $\sim 10^6$–10^8 K. The

superbubbles were found to retain as high as ~10 per cent of its input energy, for an ambient density of $10^3\,m_H\,cm^{-3}$. Comparison of these results with the observations of 30 Doradus showed that at early times the dynamics of 30 Doradus is controlled by radiation pressure.
[Siddhartha Gupta, Biman B. Nath, Prateek Sharma and Yuri Shchekinov]

Molecule formation in starburst nuclei

Recent observations had detected molecular outflows in a few nearby starburst nuclei. RRI researchers have worked out the basic physical processes related to molecule formation, destruction and suppression in the environment of a central star cluster in a disk galaxy. Parameters like disc scale height, mass of the central star cluster, star formation rate, and its surface density that could support molecule formation were determined and compared with observed parameters.

Recent observations had detected molecular outflows in a few nearby starburst nuclei. Research undertaken at RRI on the physical processes at work in such an environment resulted in a scenario that explained the observed parameters of the phenomenon, such as the molecular mass, speed and size of the outflows. The study showed that outflows triggered by OB associations, with $N_{OB} \geq 10^5$ (corresponding to a star formation rate (SFR) $\geq 1\ M_\odot\ yr^{-1}$ in the nuclear region), in a stratified disc with mid-plane density $n_0 \sim 200$–$1000\ cm^{-3}$ and scale height $z_0 \geq 200(n_0/10^2\,cm^{-3})^{-3/5}$ pc, can form molecules in a cool dense and expanding shell. The associated molecular mass was $\geq 10^7\ M_\odot$ at a distance of a few hundred pc, with a speed of several tens of km s^{-1}. A SFR surface density between $10 \leq \Sigma SFR \leq 50\ M_\odot\ yr^{-1}\ kpc^{-2}$ favored the production of molecular outflows, a range consistent with observed values.
[Arpita Roy, Biman B. Nath, Prateek Sharma and Yuri Shchekinov]

Studying the X-ray AGN halo model with eROSITA

X-ray emission from active galactic nuclei (AGN) is a major component of the extragalactic X-ray sky. It is usual to employ a halo occupation distribution model in order to understand this X-ray background. Research during the past year was geared towards understanding how the eROSITA mission planned for the near future will help in constraining the model parameters of this halo occupation model for X-ray AGNs. Such a study undertaken with a long-term vision of cross-correlating the X-ray emission from galaxies with SZ effect will enable foreground subtraction of AGN X-ray emission resulting in a better understanding of the circumgalactic medium.
[Priyanka Singh, Alexandre Refregier, Subhabrata Majumdar and Biman B. Nath]

How clustered supernovae evolve?

With the help of 3-D high-resolution numerical hydrodynamics, theorists at RRI have worked out how clustered supernovae evolve and form a single bubble. Observational diagnostics such as H-alpha, H-beta and X-ray emission during the intermediate stage when supernovae begin to merge were determined. Such a study will enable observers to distinguish this merging phase in the evolution of superbubbles.

One area of research over the past year has been on using 3D hydrodynamic simulations to study the merging and evolution of isolated supernova (SN) remnants in a stellar cluster into a collective superbubble. Attention was focused on the transition stage when the isolated SN remnants gradually combine to form a superbubble. It was found that when the SN rate is high ($\nu_{sn} \sim 10^{-9}\ pc^{-3}\ yr^{-1}$), the merging phase lasts for $\sim 10^4$ yr, for n = 1–10 cm^{-3}, and the merging phase lasts for a longer time (~0.1 Myr or more) for lower SN rates ($\nu_{sn} \leq 10^{-10}\ pc^{-3}\ yr^{-1}$). Simulations showed that most of the energy of the growing superbubble is radiated away during the merging process. It was also inferred that after passing through the intermediate phase, the superbubble eventually settles on to a new power-law wind asymptote that is smaller than estimated in a continuous wind model resulting in a significant (more than several times) underestimation of the mechanical luminosity needed to feed the bubble. Determination of the X-ray and Hα surface brightness as functions of time for such merging SNe in a stellar cluster revealed that clusters with high SN rate shine predominantly in soft X-rays and Hα. This study showed that a low value of the volume-averaged Hα-to-Hβ ratio and its large spread could be a good indicator of the transition phase of merging SNe.
[Evgenii O. Vasiliev, Yuri A. Shchekinov and Biman B. Nath]

Fermi bubbles

Past research at the Institute had provided an explanation for the Fermi bubbles from star formation at the center of the Milky Way. Recent research has added to that knowledge base by comparing the observables between the case of a bubble driven by star formation and by a jet from black hole related processes. Additionally, they were able to discriminate between the models by using the recently determined OVII/OVIII line ratios. They were also able to estimate the age of the bubbles to be 15-25 Million years.

Recent research at RRI has constrained the origin of Fermi bubbles using 2D hydrodynamical simulations of both star formation-driven and black hole accretion-driven wind models to be due to a star formation rate of ~0.5 M⊙ yr^{-1} at the Galactic Centre or a very low-luminosity jet/accretion

wind arising from the central black hole. Comparison of these results with recent observations of the OVIII to OVII line ratio within and near Fermi bubbles suggested that independent of the driving mechanisms, a low-luminosity ($L \sim 0.7\text{-}1 \times 10^{41}$ erg s^{-1}) energy injection best reproduces the observed line ratio for which the shock temperature is $\approx 3 \times 10^6$ K. Assumption of the Galactic halo temperature to be 2×10^6 K gave an estimate for the shock velocity to be ~300 km s^{-1} for a weak shock and the corresponding estimated age of the Fermi bubbles to be ~15–25 Myr. The analysis ruled out any activity that generates an average mechanical luminosity $\gtrsim 10^{41}$ erg s^{-1} as a possible origin of the Fermi bubbles.
[Kartick C. Sarkar, Biman B. Nath and Prateek Sharma]

Stellar Dynamics in Galactic Nuclei

In past years theorists in the AA group at RRI have been engaged in a three-part work that aims at providing firm foundations for the dynamical and statistical mechanical theory of Keplerian stellar systems (whose mass M is smaller than the mass M_b of their black holes). The mass ratio $\varepsilon = (M/M_b)$ is a natural small parameter that quantifies a separation of times scales: the fast Kepler orbital times and the secular time scale which is longer by a factor $(1/\varepsilon)$. In Part I of the work, a theory describing secular collisionless dynamics by describing the stellar system with a distribution function (DF) in 6-dim phase space, obeying the collisionless Blotzmann equation was formulated. Building on this, in Part II a statistical mechanical theory of Resonant Relaxation (RR) based absolutely on first principles derived by extending Gilbert's general theory of collisional evolution to include the Keplerian field of a black hole, and then specializing to a self-gravitating Keplerian stellar system was developed. The RR theory was then applied in Part III to the evolution of an axisymmetric stellar disc orbiting a massive black hole. Explicit formulae were derived for the loss cone rates of the stellar disc at which it loses its mass, energy and angular momentum to the black hole.

Focus during 2016-17 was on demonstrating the power of the theory by successfully applying it to two problems that are not tractable without it. Model problems regarding the dynamics and statistical mechanics of astrophysical discs were identified and investigation of non-axisymmetric instabilities, their time evolution and saturation, secular thermodynamic equilibrium states of axisymmetric discs, kinetic evolution of an arbitrary state and relaxation to equilibrium were carried out. The theory was also applied to a more astrophysical problem: of the response of a stellar, spherical density cusp at the Galactic Centre, to a growing ring of gas. The theory allowed construction of simple analytical models, which showed a toroidal density deformation. Of particular interest has been a population of resonantly captured stars and the overall secular stability of the system.
[J.Touma, K.Kaur, M.Kazandjian and S Sridhar]

Cosmology

Analysis of MWA EoR tracking data: delay spectrum with imaging arrays

RRI cosmologists working in close collaboration with the international MWA EoR team have proposed a general method, based on the delay spectrum approach, to extract HI power spectra that are applicable to tracking observations using an imaging radio interferometer (Delay Spectrum with Imaging Arrays (DSIA)). The method, based on modeling the HI signal, takes into account the impact of wide field effects such as the w-term, which are then used as appropriate weights in cross-correlating the measured visibilities. This method is applicable to any radio interferometer that tracks a phase center and could be used for interferometers such as MWA, LOFAR, GMRT, PAPER and HERA. So far the delay spectrum approach has been implemented for near-redundant baselines using drift scan observations. In a first of its kind, the delay spectrum approach was applied to non-redundant tracking arrays to extract the HI signal. Both 2-dimensional $(k_\parallel, k_\perp)$ and 1-dimensional (k) power spectra obtained after analyzing 3 hours of MWA tracking data on the EoR1 field were found to be in agreement with the findings of other pipelines developed to analyze the MWA EoR data.
[Sourabh Paul, Shiv Sethi and the international MWA EoR team]

Alternative dark matter models and CMB spectral distortion

Notwithstanding numerous astronomical and experimental searches, the precise particle nature of dark matter is still unknown. The standard Weakly Interacting Massive Particle (WIMP) dark matter, despite successfully explaining the large-scale features of the universe, has long-standing small-scale issues. The spectral distortion in the Cosmic Microwave Background (CMB) caused by Silk damping in the pre-recombination era allows one to access information on a range of small scales $0.3\ \text{Mpc} < k < 10^4\ \text{Mpc}^{-1}$, whose dynamics can be precisely described using linear theory. Research during the past year investigated the possibility of using the Silk damping induced CMB spectral distortion as a probe of the small-scale power. Four alternative dark matter candidates—Warm Dark Matter (WDM), Late Forming Dark Matter (LFDM), Ultra Light Axion Matter (ULA) dark matter and charged decaying dark matter (CHDM) were considered since the matter power in all these models deviate significantly from the ΛCDM model at small scales. Comparison of the computed spectral distortion of CMB for these alternative models with the ΛCDM model revealed that the main impact of alternative models is to alter the sub-horizon evolution of Newtonian potential, which affects the late-time behavior of spectral distortion of CMB. The CMB distortion y-parameter diminishes by a few percent as compared to the ΛCDM model for a range of parameters of

these models: LFDM for formation redshift $z_f = 10^5$ (7%); WDM for mass $m_{wdm} = 1$ keV (2%); CHDM for decay redshift $z_{decay} = 10^5$ (5%); ULA for mass $m_a = 10^{-24}$ eV (3%). The detectability of this deviation in the light of the upcoming CMB experiment PIXIE, which might have the sensitivity to detect this signal from the pre-recombination phase, was also considered.
[Abir Sarkar, Subinoy Das and Shiv Sethi]

Theoretical Modeling of Astrophysical Sources

Blazars are AGNs oriented in such a way that the jets of electromagnetic radiation resulting from the in falling of material into the supermassive black hole are directed towards Earth. Blazars have relativistic jets directed toward us where the radiation losses from the relativistic electrons and protons result in the emission of photons of radio to gamma ray frequencies. They are powerful sources of GeV-TeV gamma rays, which are studied using high energy gamma ray detectors. Astrophysicists at RRI have explored the high energy and very high energy phenomena in the universe with gamma ray, neutrino and cosmic ray data and have theoretically interpreted the observational results and provided estimates for the jet power related to synchrotron emission of electrons and protons.

Single zone synchrotron model and long term light curve studies for flares of PK1510-089

PKS 1510-089 is one of the most variable blazars. Very high energy gamma ray emission from this source was observed by H.E.S.S. during March-April 2009 and by MAGIC from February 3 to April 3, 2012 quasi-simultaneously with multi-wavelength flares. The spectral energy distributions of these flares have been modeled earlier with the external Compton mechanism, which depends on our knowledge of the densities of the seed photons in the broad line region, the dusty infrared torus or a hypothetical slow sheath surrounding the jet around the radio core.

Using a single zone lepto-hadronic model, researchers at the Institute have modeled the multi-wavelength data during flaring of PKS 1510-089. The lower energy peak was attributed to electron synchrotron mechanism whereas the proton synchrotron mechanism was employed for explaining the higher energy bump. The single zone lepto-hadronic model, unlike the previous models, does not require external sources of photons to explain the observed spectra. Additionally it was shown that to explain the multi wavelength data with synchrotron emission of electrons and protons the jet power should be of the order of 10^{48} ergs/s.
[Partha Pratim Basumallick and Nayantara Gupta]

A Long Term Study of the temporal and spectral properties of several flares of the highly variable source PKS1510-089 at GeV Energies collected over a period of 8 years from August 2008 to December 2016 with the Fermi-LAT has expanded the knowledge base leading to a better understanding of this particular class of blazars.
[Raj Prince, Pratik Majumdar and Nayantara Gupta]

Constraints on Proton Synchrotron Origin of Very High Energy Gamma Rays from Extended Jet of AP Librae

The multi-wavelength photon spectrum from the BL Lac object AP Librae extends from radio to TeV gamma rays. The X-ray to very high-energy gamma ray emission from the extended jet of this source has been modeled earlier with inverse Compton (IC) scattering of relativistic electrons off the CMB photons. The IC/CMB model requires the kpc scale extended jet to be highly collimated with bulk Lorentz factor close to 10. Research during the past year was geared towards exploring the possibility of proton synchrotron origin of X-rays and gamma-rays from the extended jet with bulk Lorentz factor 3. This scenario requires of AP Librae an extreme energy of protons and a high magnetic field of 0.95 mG of the extended jet with Poynting power more than 100 times Eddington's luminosity.
[Partha Pratim Basumallick and Nayantara Gupta]

Observational Astronomy

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

Radio Astronomy

Low-frequency Investigation of the Subpulse Drifter PSR J0034-0721 with the Murchison Widefield Array

The phenomenon of subpulse drifting may hold the key to understanding the pulsar emission mechanism. Recent observations of PSR J0034-0721 (B0031-07) carried out with the Murchison Widefield Array at 185 MHz has shown three distinct drift modes whose "vertical" drift band separations (P3) and relative abundances are consistent with previous studies at similar and higher frequencies. The drift bands, however, were observed to change their slopes over the course of individual drift modes, which was interpreted as a continuously changing drift rate. The implied acceleration of the intrinsic carousel rotation cannot easily be explained by plasma models based on ExB drift. Furthermore, it was found that methods of classifying the drift modes by means of P3 measurements could sometimes produce erroneous identifications in the presence of a changing drift rate. The "horizontal" separation between drift bands (P2) was found to be larger at later rotation phases within the pulse window, which is inconsistent with the established effects of retardation, aberration, and the motion of the visible point. Longer observations spanning at least 10,000 pulses are required to determine how the carousel rotation parameters change from one drift sequence to the next.
[S.J. McSweeney, N. D. R. Bhat, S. E. Tremblay, Avinash Deshpande and S. M. Ord]

Signatures of occultation of radio sources

Lunar occultation of radio sources has been studied extensively, and has been used in the past for estimating sizes/structure of extragalactic sources. However, the spectro-temporal signatures of this phenomenon have rarely been discussed, let alone studied in detail. Inspired by recent detection of fast radio bursts, radio astronomers at RRI have taken a closer look at the occultation of radio sources, and explored the possible signatures this would produce in the dynamic spectra. For a partially occulted source, there is a frequency dependent temporal variation in the intensity as the source direction changes with respect to the diffracting edge. A detailed study of the dependence of this signature on the source size, and the way source direction may change with time has shown that in certain situations, a dispersion like trend can be produced in the dynamic spectrum, but the time scales of intensity increase and that of the delay gradient cannot together be in the desired ranges of parameters associated with fast radio bursts.
[Jigisha Patel and Avinash Deshpande]

A new method for searching off-pulse radio emission from pulsars

A new method that is immune to confusion from other sources in the field of observation, and also to possible artifacts due to receiver imperfections, has been explored in detail and proposed as an effective tool for searching and detecting unpulsed emission intrinsic to pulsars. The method has been successfully tested with data from Green Bank Telescope taken using RRI-GBT Multi-band Receiver System.
[Kumar RaviRanjan and Avinash Deshpande]

A study of halo and relic radio emission in merging clusters using the Murchison Widefield Array

Using the Murchison Widefield Array (MWA) radio astronomers at the Institute have studied radio haloes and relics in nine merging galaxy clusters and detected diffuse radio emission in eight of these clusters. The images used for this study were obtained from the Galactic and Extragalactic All-sky MWA (GLEAM) Survey, which was carried out at five frequencies, viz. 88, 118, 154, 188 and 215 MHz. An estimate of the spectra of haloes and relics in these clusters over the frequency range 80-1400 MHz, the first such attempt of its kind at low frequencies, revealed that the spectra follow a power law with a mean value of α = -1.13 ± 0.21 for haloes and α = -1.2 ± 0.19 for relics, where the flux density $S \propto \nu^{\alpha}$. Using the low-frequency spectra two of the cluster sources were classified as radio galaxies, five of the nine clusters were found to host radio haloes. Additionally the low-frequency spectra enabled upper limits to be placed on the radio powers of possible haloes in the remaining four clusters. These upper limits were a factor of 2-20 below those expected from the L_X - $P_{1.4}$ relation. These limits are the lowest ever obtained with possible implications for the hadronic model of halo emission.
[L.T. George, K.S. Dwarakanath and the MWA collaboration]

HI, star formation and tidal dwarf candidate in the Arp 305 system

The Giant Metrewave Radio Telescope (GMRT) was used for HI observations of the Arp 305 system. The system consists of two interacting spiral galaxies NGC 4016 and NGC 4017, a large amount of resultant tidal debris and a prominent tidal dwarf galaxy (TDG) candidate projected within the tidal bridge between the two principal galaxies. The higher resolution GMRT HI mapping, compared to previous observations, enabled detailed study of smaller scale features and supports the conclusion in Hancock et al (2009) that the most recent encounter between the pair occurred $\sim 4 \times 10^8$ yrs ago. The observations also show HI features near NGC 4017,

which may be remnants of an earlier encounter between the two galaxies. The HI properties of the Bridge TDG candidate: M(Hi) ~ 6.6×10^8 M_o and V(Hi) = 3500± 7 km/s was in good agreement with the velocities of the parent galaxies. Additionally, the TDG's HI linewidth of 30 km/s and a modest velocity gradient together with its SFR of 0.2 Mo /yr add to the evidence favoring the bridge candidate being a genuine TDG. The Bridge TDG's Spitzer 3.6 μm and 4.5 μm counterparts with a [3.6]–[4.5] color ~ -0.2 mag suggests stellar debris may have seeded its formation. Future spectroscopic observations could confirm this formation scenario and provide the metallicity, which is a key criterion for the validation for TDG candidates.
[C. Sengupta, T. C. Scott, S. Paudel, K. S. Dwarakanath, D. J. Saikia and B. W. Sohn]

First light from SARAS-2

Long wavelength spectral distortions in the Cosmic Microwave Background arising from the 21-cm transition in neutral Hydrogen are a key probe of Cosmic Dawn and the Epoch of Reionization. These features may reveal the nature of the first stars and ultra-faint galaxies that transformed the spin temperature and ionization state of the primordial gas. SARAS-2 is a spectral radiometer purposely designed for precision measurement of these monopole or all-sky global 21-cm spectral distortions. Using a 4-hr observation of the radio background in the frequency band 110-200 MHz with the radiometer deployed at the Timbaktu Collective in Southern India, astronomers at the Institute derive likelihoods for plausible redshifted 21-cm signals predicted by theoretical models. First light with SARAS 2 disfavors models that feature weak X-ray heating along with rapid reionization.
[Saurabh Singh, Ravi Subrahmanyan, Udaya Shankar, Narayana Rao, Mayuri S Rao, Anastasia Fialkov, Aviad Cohen, Rennan Barkana, B.S. Girish, A. Raghunathan, R. Somashekar, and K.S. Srivani]

Fathoming radio galaxy phenomenon on the smallest to largest scales via multi-band radio imaging

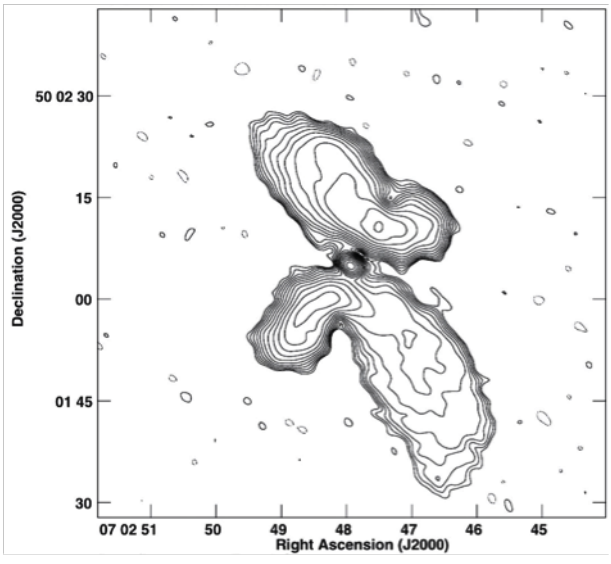
Given the relatively large radiative lifetimes of relativistic electrons in synchrotron plasmas that constitute radio galaxy lobes, radio galaxies form valuable tools for understanding hard-to-probe processes happening at the very innards of their host galaxies that are responsible for creating and sustaining the radio galaxy phenomenon. The 'central engine', that is at the heart of a centrally located active galactic nucleus (AGN), which comprises of a $10^7 – 10^9$ solar mass supermassive black hole and a plasma disk that accretes on to it, is responsible for generating twin jets of relativistic plasma. These jets transport synchrotron plasma at relativistic speeds, which ultimately result in a wide variety of radio galaxy morphologies and powers, which can reach linear scales from sub-parsecs to several mega-parsec scales.

Radio astronomers at the Institute in collaboration with international peers have imaged a large, select sample of radio galaxies with the Very Large Array (VLA, USA) with the purpose of classifying the variety in large-scale radio galaxy morphologies and to use them together with component spectral ages and polarization distribution towards answering questions related to perturbations to the central supermassive black holes and to infer causes and estimate timescales involved in the perturbative processes. The total intensity and polarization images of radio galaxies not only reveal a variety in morphological types (beyond the typically seen twin-lobe structures that straddle central radio cores in radio galaxies) but also reveal specific patterns to the different radio morphologies. This exercise is among the first steps towards inferring causative factors for generating the atypical morphologies that have been imaged in the sources and hence to also probe the central engine behavior. With sensitive and high resolution data revealing strongly inversion symmetric structures in almost all sample sources this work already points to possible causative factors associated with the central engine.

Black hole spin evolution is seen as an important ingredient in black hole growth and mass evolution through cosmic times. Together with spin direction, whether prograde or retrograde with respect to the accreting gas, spins affect black hole mass gain per accretion event and mass to energy conversion efficiency. In tandem with the close relationships between black hole spin, its mass growth rate and mass to energy conversion efficiency are the orientation of black hole axis, relative angular momentum between accretion disk and black hole as well as relative axis alignments, all of which have received only little attention in such studies. With jet formation models, simulations and observations having gained in sophistication over the years, central black hole spins are increasingly seen as playing a key role in the generation of twin jets in radio galaxies. With the twin jets creating the extended radio structures along their axis out to several hundred kilo parsec scales (and hence lending themselves easily to imaging) radio galaxies form valuable tools in providing a handle on spin axis orientation and temporal behavior, which is otherwise difficult to study.

Although inferences of changes to central black hole axes in radio galaxies have been made previously, these were based on serendipitous and fortuitous detections of distorted structures. RRI astronomers and collaborators have employed a large and select radio galaxy sample to comprehensively map the variety in radio morphologies so as to track jet axis changes, if any. Examination and characterization of the source radio structures has resulted in obtaining a handle on the morphological variety that exists as well as occurrence rates for

the different axis change types inferred in the sample sources. Detailed total intensity, polarization and radio (and optical) spectral information to model the source axis changes were employed to derive axis rotation speeds, timescales and angles over which axis changes have taken place.



The figure shows the radio galaxy J0702+5002 imaged at frequency 2999 MHz with the VLA. The radio galaxy has large off-axis emission 'wings' oriented at a large angle with respect to the main lobes. This is one of 100 such sources we have imaged to understand the location of significantly off-axis emission, which will be used to probe the central black hole behaviour.

The multi-frequency radio VLA imaging project of the 100-source sample that was proposed commenced in mid 2015 and saw completion in late 2016. RRI astronomers and collaborators analyzed and imaged the data to produce multi-frequency images of radio galaxies in the sample. The polarization and spectral index data reduction although also completed, will be taken up for detailed analysis and interpretation at a later date. The multi-frequency images for each of the 100 sources has yielded a wealth of information on the structures of sources in the unique sample - rotationally symmetric structures are dominant and the structural symmetries are such that they appear to originate from strategic locations along the radio axis - either the outer ends of jets or inner ends of lobes or the off axis radio emission forms a central swath through the host galaxy across the main radio axis (see accompanying figure showing one of the mapped radio galaxies). A large sample and sensitive multi-frequency radio imaging enabled derivation of robust occurrence rates for the three types of radio structural distortions. The work has shown that radio galaxies with off-axis distortions originating from the inner lobe ends are most common and are associated with the most powerful radio sources. Detailed examination and characterization of individual source structures noting component features such as presence of hotspots, transverse off axis extensions, their linear extents, non-collinearities, optical spectra, source powers, lobe extent asymmetries were undertaken along with detailed study of correlations between them. These exercises provided inputs with which to examine proposed scenarios for formation of off-axis sources. The work helped in discriminating between models, paving the way for more targeted exercises with which to examine source structures.

With detailed structures now available for most of the 100 sources efforts are on to unravel patterns to the relationship of off-axis emission with their main radio sources, which allows to explore and present frameworks for the origin of this emission that is located significantly offset from the main radio axis.
[David H Roberts, Ravi Subrahmanyan, Mayuri S Rao and Lakshmi Saripalli]

X-ray Astronomy

Discovery of a massive circum-binary planet around an X-ray binary MXB 1658-298

Recent research was on X-ray timing analysis of a transient X-ray binary MXB 1658– 298, using data obtained from the RXTE and XMM–Newton observatories. A combination of 27 new mid eclipse time measurements along with previously known values used to study the long term changes in orbital period of the binary system revealed an unusual mid eclipse timing of MXB 1658-298. The long-term evolution of mid-eclipse times indicated an overall orbital period decay with a time scale of $6.5(7) \times 10^7$ year. Over and above this orbital period decay, the O-C residual curve also showed a periodic residual on shorter timescales. This sinusoidal variation had amplitude of ~9 lt-sec and a period of ~760 d, which is indicative of the presence of a third body around the compact X-ray binary. The mass and orbital radius of the third body were estimated to lie in the range, 20.5–26.9 Jupiter mass and 750-860 lt-sec, respectively. If true, this will be the most massive circum-binary planet and also the smallest period binary known to host a planet.
[Chetana Jain, Biswajit Paul, Rahul Sharma, Abdul Jaleel and Anjan Dutta]

A deep look at the intriguing binary X-Persei with a long Suzaku observation

Detailed broadband timing and spectral analysis of the persistent, low luminosity and slowly spinning pulsar X Persei using a long Suzaku observation of the source have enabled the best constraint on the broadband spectral model of X Persei obtained so far. The X-ray spectrum of X Persei is unusually hard with a cyclotron resonance scattering feature (CRSF) at ~ 30 keV, the presence of which has been debated. The CRSF is

not confirmed in the average spectrum. The presence of different intensity levels in the source with distinct changes in the pulse profile and energy spectrum has been identified, which is indicative of changes in the accretion geometry. Further evidence of a CRSF in the highest intensity levels at ~ 40 keV indicate a magnetic field strength of 3.4×10^{12} G.
[Chandreyee Maitra, Harsha Raichur, Pragati Pradhan and Biswajit Paul]

Orbital modulations in the highly obscured sgHMXB IGR J16318-4848

IGR J16318-4848 is an X-ray binary with the highest known line of sight absorption column density among all known X-ray binary systems in our galaxy. RRI astronomers investigated the reason behind such a large absorption column by looking at the variations in the X-ray intensity and spectral parameters as a function of the recently discovered ~80 day orbit of this source revealed two peaks in the orbit intensity profile about half an orbit apart, one narrow and small, and the other broad and large. It was found that the larger peak is a result of randomly occurring large flares spread over ~0.2 orbital phase, whereas the smaller peak was seen in each and every orbit as a regular increase in intensity. Using archival data spread over different phases of the orbit and the geometry of the system as obtained from previously published infrared observations, a possible scenario was proposed to explain the nature of this X-ray binary.
[Nirmal Iyer and Biswajit Paul]

Changes in the pulse phase dependence of X-ray emission lines in 4U 1626-67 with a torque reversal

Recent research at the Institute involved a long observation of a unique X-ray pulsar 4U 1626–67 with the XMM-Newton observatory. EPIC-pn data during the current spin-up phase of 4U 1626–67 was used to study pulse phase dependence of low energy emission lines. The observation showed strong variability of low energy emission lines with the pulse phase, varying by a factor of 2-10, much stronger than the continuum variability. Another interesting observation is that behavior of low energy emission lines across the pulse phase were quite different from that observed during the spin-down phase. This indicates that the structures in the accretion disk that produce pulse phase dependence of emission features have changed from spin-down to spin-up phase. This is well supported by other already known differences between spin-down and spin-up phases. An additional new difference found from this observation is that below 2 keV, the X-ray pulse profile in the spin-up phase is quite different compared to the spin-down phase. The X-ray light curve also shows flares which produce a feature around 3 mHz in the power density spectrum of 4U 1626–67.
[Aru Beri, Biswajit Paul and Gulab Dewangan]

ASTROSAT observations
During the past year, astronomers at the Institute have analysed ASTROSAT-LAXPC data from many observations of various kinds of sources like: i) PSR 1509-586 to study its spectral parameters of the pulsed component, ii) Vela X-1 to study its pulse profile over a wide energy band and study of the cyclotron line at different pulse phases, and iii) 4U 1636-26, in which they have detected a rare and rapid triplet of thermonuclear bursts and carried out time resolved burst spectroscopy.
[Varun, Pragati Pradhan and Aru Beri]

Design, Construction and Operation of telescopes

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. Additionally, new methods and modeling 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.

An Efficient Linear-array Imager prototype for molecular astronomy

Imaging surveys covering large sky areas are important to advance astronomy. The 35 MHz continuum survey with the T-array at Gauribidanur was carried out by RRI decades ago. Recently, efforts are being made at the Gauribidanur field-station to build a cm-wave imaging telescope. This is a prototype of the new optics scheme proposed some years ago: "An Efficient Linear-array Imager (ELI) for radio astronomy", 2014, MNRAS, v.444 p.2212, which promises ease and economy of manufacturing.

In this novel optics scheme, given a certain number of receivers, one can image the sky for the same time, resolution and sensitivity with lesser reflector area than a corresponding single dish. Moreover, the smaller reflector area is shaped as parabolic cylinders, easy and economical to manufacture. The area reduction arises as follows: in a conventional paraboloidal telescope, say with 16 receivers, one can instantaneously observe over 16 circular beams on the sky. In the new optics scheme proposed by RRI astronomers, the receivers make highly elliptical beams, which are arranged equally as adjacent rows and columns, as in a matrix. Then, by cross-correlating the outputs of the row receivers with the column receivers, one can obtain 64 pencil beams, corresponding to the cells of the matrix. The very process of making the beams elliptical reduces the reflector area to 70%!

Over the year, astronomers at the Institute have developed and optimised the telescope backup structure and successfully designed and developed from scratch a light-weight and stiff backup structure for the 6.8 m x 6.8 m prototype cross telescope. The backup structure weighs 225 kg for a maximum deviation of ~1 mm when loaded with the primary and secondary panels, themselves weighing about 360 kg. Similar would be the expected deviations for wind-loads at 10 m/s speed. Salient and novel design features are: (a) large counter-weights are avoided by designing the elevation axis closer to the center of mass of the system, (b) side-sections have been made rigid and light with a horizontal track and ball mechanism, (c) 180° travel in elevation has been made possible with an automatic pier crossing interlink between the two side sections. Currently, a scale-model is being built at the RRI field station at Gauribidanur. Accompanying figure shows the CAD model view of the telescope backup structure, including the mirrors. A photo of the scaled model of the backup structure under construction is shown. Soon the construction of the full version will begin, to demonstrate the feasibility and utility of the concept. To demonstrate its working, 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.
[Swaroop Jois, Ashwini Prakash, Charles Paul and Ramesh B]

X-ray Polarimeter

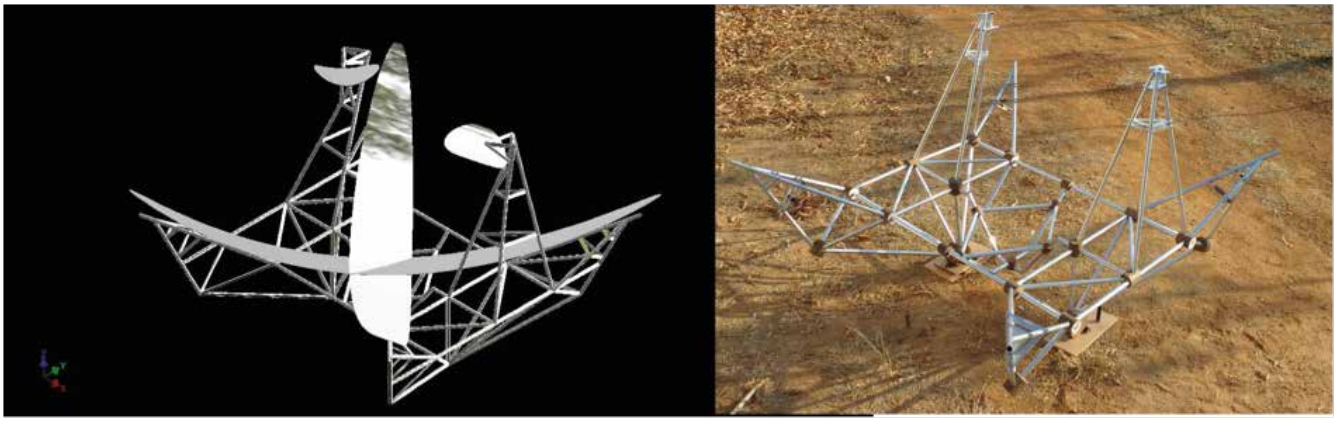
This has been a busy year with many activities for the Thomson X-ray polarimeter experiment POLIX. An MOU between RRI and ISRO for POLIX onboard XPoSat has been prepared. In collaboration with the XPoSat project office, there has been significant progress in defining the interfaces between the payload and the satellite. In addition, the following developments have taken place at RRI on POLIX hardware:

• One detector with a wire frame has been successfully tested for vibration.
• Components have been made for environmental (thermal and vacuum) tests of the high voltage unit.
• An X-ray beam-line for calibration of the collimator has been designed and partially installed.
• PCBs for the Processing Electronics and Common Electronics units of POLIX have been fabricated and their functional tests completed.
• Significant progress made in identifying and procuring components for flight electronics of POLIX.
• Method for finite element model and finite element analysis of POLIX payload have been finalized and the work is in progress.
• Design of space qualified electronics housing has been done and fabrication of one unit is in progress.
• Accommodation study of POLIX payload components on the XPoSat satellite deck has been completed and assembly design has been made.

[P. V. Rishin, M. R. Golapakrishna, Mohamed Ibrahim, Abhilash Kulkarni, Pooja Verma, G. Rajagopala, T. S. Mamatha, P. Sandhya, H. N. Nagaraja, Nirmal Iyer, Varun, Biswajit Paul and many members of MES have made major contributions to all the development work.]

System design for prototype element of APSERa

APSERa – Array of Precision Spectrometers for the Epoch of Recombination, is an experiment aimed at detecting the very weak signals of cosmological hydrogen and helium recombination. These cosmological spectral lines are a signature of the formation of the very first neutral atoms in the early Universe. APSERa operates over 2-4 GHz. The prototype element of the array is currently being developed in-house at RRI. The system architecture is comprised of an



(Left) A CAD model view of the backup structure, with the mirrors set. (Right) A photo of the scaled-model of ELI, 2.3m x 2.3m, being built at Gauribidanur.

antenna connected to analog receiver electronics followed by digitization and correlation in a precision digital spectrometer. A short dipole antenna has been custom designed and tested with results matching simulations. Further improvements in antenna design are required to make the antenna more robust for field use. Such a custom designed antenna is required to have properties conducive to signal detection.

A system bandpass calibration scheme has been arrived at, which will guide analog receiver design. This scheme is aimed to minimize leakage from the two signal paths in the architecture by converting the signal from the antenna to optical at the earliest possible stage. Towards this precision spectrometer, a prototype 2 GHz digital correlation spectrometer interlaced sampling scheme has been achieved. Interlacing of Analog-to-Digital converters (ADCs) can result in artifacts that appear as spurious signals in measured spectra. Correction to reduce the levels of these unavoidable spurious features calls for ADC calibration. Such an ADC calibration pipeline has been created, tested and successfully implemented. With this, digital correlator is ready for integration with the analog chain for complete system testing. [Mayuri S Rao, Jishnu Nambissan, Ravi Subrahmanyan, N. Udaya Shankar, B.S. Girish, A. Raghunathan, R. Somashekar, and K.S. Srivani]

SWAN Phase-0: A narrow-band 8-tile system for initial proof-of-concept

The development of SWAN Phase-0 system has progressed well in the past months. As planned, the RRI-GBT receivers (recalled from GBT) had arrived, 8 of the 10 pipelines are reconfigured and now installed at our field-station at Gauribidanur (GBD), about 80 km from Bangalore. These are connected to the (MWA) antenna tiles (already moved there), configuring initially to form an 8-station tied-array system shown in Figure 1 (with a common frequency standard), for testing the desired functionality first in this mode.

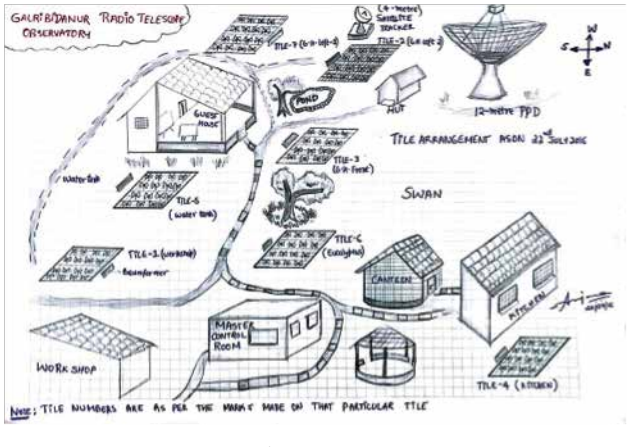


Figure 1 Tile arrangement at GB

The SWAN 8-tile (each tile consists of crossed 16 elements) bow-tie antenna array currently existing in GBD field station has been refurbished with new replacements. This process involved the following tasks

1. Few of RF low noise amplifiers (80MHz-330MHz), which are a part of each bow-tie antenna element, were malfunctioning due to bad environmental weather conditions. Each of these amplifiers were located and then rectified for proper reasons of failure.
2. The RF cables of equal lengths connecting each antenna element to the beamformer input were in bad shape due to environmental variations. These RF cables were replaced by new ones, which are having the same dielectric constant, electrical and RF characteristics as the original ones.
3. The beamformed RF output signal from each of the beamformers from 8 tiles are carried all the way to the receiver room through a 75 ohm CATV cable, where the 80-330 MHz spectral signal is connected to the existing GBT-RRI narrow band receiver through an impedance conversion device for further processing. These cables, which connect the beamformer RF output connector to the receiver system, were replaced by new similar cables with sturdy connectors.
4. A beam - former unit (preferably placed close to the tile, so as to save on overall cable lengths), combines a set of inputs received from 16 array elements after introducing programmable relative delays (through computer-control), and provide a single output per polarization. At present, all beam-former controls are derived from a common parallel-port of one PC.

In continuation with the above refurbishment of the tiles and it's inter connectivity, the RF signal is being processed through the MBR narrow band receiver system having instantaneous bandwidth of 140 MHz for astronomical observations using a software correlator.

The software correlator, which sets the basis for aperture synthesis imaging, is being developed in C. The pipeline generates complex numbers, which are visibilities measured on a set of interferometer baselines, which use an FX style correlation with user-specified integration, puts them on a spatial frequency (U,V) map, and performs a 2-D Fourier transform which gives the dirty image. Some of the important features of the program are as described below:

1. Ability to handle packet slips in the raw data.
2. A routine that invokes a Hilbert transform method o plot and determine the intra packet and intra sample delay.
3. A routine to plot dynamic spectra (Figures 3 & 4), which can be used to observe and analyze fringes.
4. Many of the functionality can be used on sniff mode raw data as well.
5. A synchronization algorithm which uses GPS count to achieve synchronization by getting the interpacket-number delay.

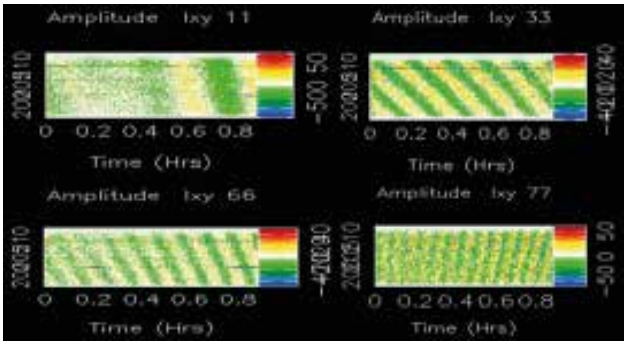


Figure 3 (Top left to bottom right - Fringe frequency or Baseline length in increasing order)

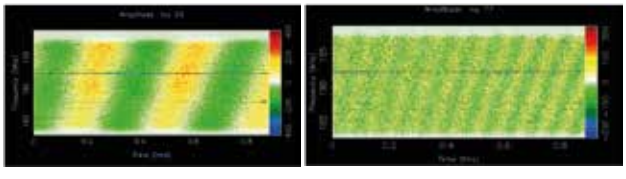


Figure 4 (left to right - Fringe frequency or Baseline length in increasing order)

Further tests will be conducted with the narrow band subsystem after providing individual frequency standards with their stand-alone Rubidium oscillator and GPS, installed at GBD.
[C. Vinutha, K. B. Raghavendra, H. A. Aswathappa, Sasi Kumar, Rahul Kinger, Anjana Kuduva, T.S. Mamatha, P. Sandhya,Nagaraja H N, Mamata Bai, Indrajit Barve, Avinash Deshpande and staff from RRI workshop, computer section and Gauribidanur field station]

Strategic development

Image of the Portable dual Receiver

Portable Dual Receiver, in continuation through the previous year, had problems related to LO leakage and ground loops. These issues were overcome by housing two separate boxes for Analog front-end and Digital back-end receivers as shown in Figure 2 and also with proper grounding channels. This receiver made use of ST-Radar arrays, which have recently been commissioned at CUSAT-Kochi and ARIES-Nainital for wind profiling, and the attractive possibility of their inclusion in the SWAN (providing larger collective area) are being actively explored.
[K. S. Srivani, S. P. Madhavi, P. A. Kamini, K. B. Raghavendra, C. Vinutha, Nagaraja H N and Avinash Deshpande]

Signal Processing and Data Analysis

Forward error correcting codes

In previous years, research at the Institute has been towards analyzing the performance of three different Forward error correcting codes (FECCs), each with multiple code rates in the range 0.5 to 1, over a range of SNR of the AWGN channel for four symbol mapping schemes and two fading types, using a common MIMO-STBC-OFDM communication link, transferring data at a base rate of 100 Mbps.

During the past year this work has been extended to include Block Product Codes. These are multi- dimensional codes that build redundancy in orthogonal directions and thereby improve the FECC efficiency. A systematic study of 2 and 3 dimensional product codes using normal and extended Hamming codes as component codes was undertaken. The hard-decision approach employed to detect and correct errors has demonstrated that building redundancy in dimensionality is better than in extending the code. The 3D hard decision decoder performs nearly as well as the AHA-TPC that uses extended 2D codes with soft decision.
[Parvathi Chandrasekhar and Ramesh B]

Towards a non-iterative search for dispersed pulses

All electromagnetic waves or radio signals undergo dispersion while passing through the interstellar medium, but the effect is measurable only in the case of pulsar or transient signals. De-dispersion techniques are routinely used for removal/correction of dispersion effects from pulsar signals, when the dispersion measure (DM) is known a priory. While searching for pulsars or fast radio transients, i.e., when DM is not known, de-dispersion has to be carried out for large number of trial DM values and the DM is identified at which the resultant de-dispersed pulse, if any, appears strongest. This is computationally intensive, particularly for data across a wide bandwidth and across a large range of DMs.

To overcome the demanding data-processing requirements, astronomers at the Institute explored new approaches for detection of dispersed pulses through a single processing step. Initial tests of the new algorithms have shown encouraging results and suitable refinements are being introduced, which

are tested on simulated and real data.
[Sourita Saha and Avinash Deshpande]

Search for pulsars and fast transients with Gauribidanur telescope

A specially tuned pipeline for processing the survey data from the Gauribidanur array at 34.5 MHz is now developed, with particular attention to reduce effects of radio-frequency interference, and to detect low-frequency radio transients, including single pulses from pulsars. Tests of the software and data analysis are in progress.
[H.A. Ashwathappa and Avinash Deshpande]

ASTROSAT-LAXPC

Recent research has been on fine tuning the data reduction pipeline software of ASTROSAT-LAXPC in collaboration with the Space Application Centre. Further work has been done at RRI to identify various kinds of previously unspecified errors in raw data of LAXPC and methods for eliminating the same or correcting the same have been found and implemented. Towards this, additional software tools have been developed. Separate light curve and spectral extraction tools have been written for faster implementation of data reduction.
[Shreenandini Anand, Jincy Devasia, Aru Beri, Varun and Biswajit Paul]

Physically motivated foreground modeling for long wavelength radio astronomy

Interest in long wavelength astronomy has been renewed due to interest in detecting signatures of the Epoch of Reionization at these wavelengths. However a major challenge in detecting the cosmological signal is the presence of foregrounds that are orders of magnitude brighter. At long wavelengths the strongest foreground is presented by emission from our own Galaxy. Although traditionally these foregrounds are modeled as a power law owing to the dominating synchrotron emission, this is a rather simplistic assumption. There exist global sky models that present a data driven method to simulate the low frequency sky, however they are not necessarily physically motivated.

Astronomers at the Institute have developed a physically motivated global sky model that incorporates electron energy distributions with breaks to generate the synchrotron component, and free-free emission and absorption as well as allowing for mixtures of sources with different spectral indices. The inputs to the model are data from all sky-maps at 150 MHz, 408 MHz, 1420 MHz and 23 GHz, as well as maps at 22 MHz and 45 MHz from available global sky models, to provide a constraint at lower frequencies. Having generated a code that does a best fit to the aforementioned input maps, the model can be used to generate all sky maps and sky spectra between 10 MHz to 23 GHz with a resolution of 5 degrees.
[Mayuri S Rao, Ravi Subrahmanyan, N Udaya Shankar, and Jens Chluba]

Application of Maximally Smooth functions for foreground subtraction for global 21-cm signal from the Epoch of Reionization

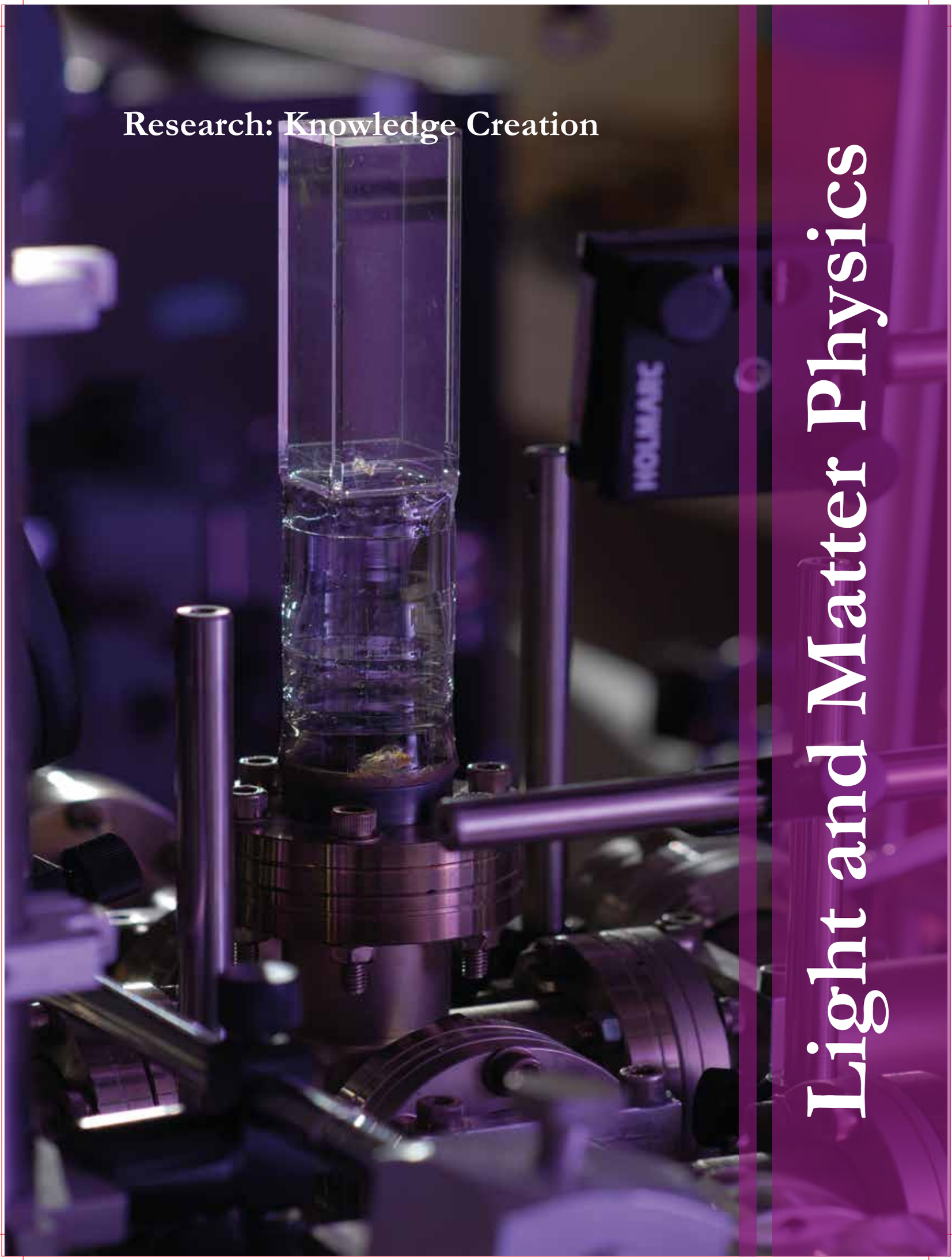
Researchers at the Institute had previously arrived at a method using 'Maximally Smooth' functions to carefully fit to the foreground and the CMB such that cosmological recombination signal could be extracted without being fitted out by the fitting function. This has been a challenging problem in various other problems in astronomy, which involve recovering a weak broad spectral feature from a sky spectrum, which is several order of magnitudes larger than the signal of interest. Efforts were undertaken during 2016-17 towards extending the application of 'Maximally Smooth' functions to distinguish between the complex foregrounds and the redshifted global 21-cm signal arising from the epoch of reionization. The radio foregrounds are expected to be smooth over the bandwidth of the predicted EoR signal (~10-200 MHz); however, the functional form of the foreground spectrum is not known to the precision required. Using polynomials of high order to model the foreground as has been described in literature could result in potentially losing a significant fraction of the EoR signal. Research at the Institute has demonstrated that adopting 'Maximally Smooth' functions preserves the EoR signal while clearly fitting the foreground alone, for the vanilla global EoR signal. There is no loss in signal with increasing the order of these smooth functions to any arbitrarily high value.
[Mayuri S Rao, Ravi Subrahmanyan, N Udaya Shankar, and Jens Chluba]

Broadband uGMRT and GMRT data analysis

During the past year, astronomers at RRI worked to establish at the Institute an automated pipeline to analyse uGMRT broadband data. This work included testing AOFlagger, an automated flagging software, and WSClean, a fast cleaning algorithm, on 200 and 400 MHz uGMRT data. Three data sets of uGMRT, which were observed with 16 antennas (400 MHz and 1200 MHz central frequencies) and one data set observed with all 30 antennas, have been analyzed so far. Comparison of the amount of time required to process such large-volume data sets (more than 50 GB) with CASA and WSClean software showed that WSClean takes only 8 to 10 hours to reduce these data while CASA takes around 48 hrs. An improvement in uGMRT sensitivity of continuum imaging by factor of three as compared to GMRT 32 MHz legacy system was seen. Currently, RRI astronomers in collaboration with SKA South Africa are working on incorporating solutions for direction-dependent effects in

low-frequency broadband uGMRT data. Efforts are ongoing to install a full working pipeline known as Stimela developed for MeerKAT (SKA precursor), at RRI.

SPAM (Source Peeling and Atmospheric Modeling) is a Python-based extension to AIPS, aimed at reducing high-resolution, low-frequency radio interferometer observations in a very efficient, systematic and reproducible way. Special features in SPAM, like direction-dependent ionospheric calibration and image-plane ripple suppression, will help to make high-quality sub-GHz images. Current research efforts are directed towards reducing low frequency GMRT (32 MHz bandwidth) data with SPAM software. Analysis of around 15 data sets of GMRT (at 150, 235, 325 and 610 MHz) with SPAM, including six GTAC observations, six clusters observations, as well as archival data has been completed. The same SPAM software is also being used to analyze six clusters observed using GMRT through the collaborative project: SoUthern Cluster sCale Extended Source Survey (SUCCESS). The primary aim of this project is to understand the ICM and testing survey strategies for the GMRT and future radio telescopes.
[K.S. Dwarakanath, Ruta Kale and Viral Parekh]



Research: Knowledge Creation

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. For example understanding the fundamental quantum aspects of light will enable super-secure communication and information transfer.

Focus 2016-17

Ultracold-atoms, ions 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 cold collisions and interactions at low temperatures. Specific focus has been towards developing new methods for cooling of ions. In a first of its kind, recent experiments showed that trapped ions of low mass could be cooled by elastic collisions with heavier neutral atoms. This experiment provided a resolution to a long-standing controversy in theoretical literature. Experiments during the past year have established a new ion cooling mechanism based on resonant charge exchange between ions and ultracold atoms. Attempts to cool Rb^+_2 molecular ions by using ultracold Rb atoms threw a surprise – it was found that Rb^+_2 ions are dissociated by the light used to cool the Rb atoms.

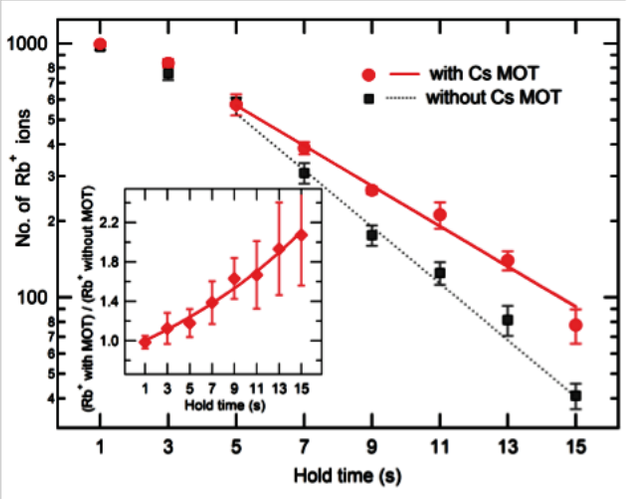
Cavity based quantum optics is another area of active research in the LAMP group. Strong interactions between neutral atoms and light can be achieved by trapping light in a high-Q cavity. This enables several aspects of strongly coupled light-matter interaction to be studied. Such trapped atom-light studies are conducted both with ultracold atoms at about 100's of microkelvin temperatures and with atoms at room temperature. Ultracold atoms were placed within a Fabry Perot cavity and the collective strong coupling between the atoms and the cavity modes were studied. The signature of such coupling is vacuum Rabi splitting (VRS) in the transmission spectrum of a weak probe beam. This system was used to demonstrate optical bistability and all-optical switching of cavity transmission. Additionally VRS was used as a non-destructive probe to detect and measure the presence of trapped ions. Such experimental studies enable RRI to make useful contributions to the worldwide effort on better understanding of interactions, cold chemical reactions, quantum phase transitions and quantum simulations.

A new experimental facility towards creating a Sodium-Potassium gas mixture at nano-Kelvin temperature was started in the LAMP group last year. At these very low temperatures the system can be an ideal test bed for investigating quantum nature of interactions between these mixtures. Such a study will throw light on critical physical principles underlying complex condensed matter systems like those that show superconductivity.

Collisions and Interactions

Collisional cooling of light ions by cotrapped heavy atoms

Over the past year LAMP staff have demonstrated, for the first time, cooling of low-mass ions by co-trapped heavier atoms. Among the different methods to cool trapped ions, cooling by elastic collisions with a cold buffer gas is arguably the most generic. Indeed, buffer gas cooling of trapped ions has been extensively used when the mass of the ion (m_{ion}) is higher than the mass of the buffer gas atoms (m_{atom}). Surprisingly, however, the counterpart, that of cooling of trapped ions when $m_{ion} < m_{atom}$, has never been demonstrated experimentally. The most likely reason dates back to a seminal work by Major and Dehmelt [Phys. Rev. 170, 91 (1968)] where it was predicted that an ion trapped in a Paul trap can be cooled by a uniform buffer gas if and only if $m_{ion} > m_{atom}$. For the broader community, this became a rule of thumb. However, recent advances in laser cooling and trapping has enabled a different class of experiments where the atomic ensemble is well localized within a trap. In such experiments with simultaneously trapped ions and atoms, the original analysis of Major and Dehmelt needed to be revisited.



This figure illustrates the lifetime of rubidium ions in the presence of a Cs MOT and thus shows the cooling of lighter mass Rb ion in collision with heavier mass Cs atoms.

RRI staff have shown that the lighter $^{39}K^{+}$ ions, created by ionizing ^{39}K atoms in a magneto-optical trap (MOT), when trapped in an ion trap and subsequently allowed to cool by collisions with ultracold, heavier ^{85}Rb atoms in a MOT, exhibit a longer trap lifetime than without the localized ^{85}Rb MOT atoms. A similar cooling of trapped $^{85}Rb^{+}$ ions by ultracold ^{133}Cs atoms in a MOT was performed using a different experimental configuration to validate this mechanism of ion cooling by localized and centered ultracold neutral atoms. These results suggest that cooling of ions by localized cold atoms holds for any mass ratio, thereby enabling studies on a wider class of atom-ion systems irrespective of their masses.
[Sourav Dutta, Rahul Sawant and S. A Rangwala]

Cooling of trapped ions by resonant charge exchange

Cooling and trapping of dilute gases, both neutral and charged, have enabled extremely precise and controlled experimentation with these systems. The two most widely used ion cooling methods are laser cooling and sympathetic cooling by elastic collisions (EC). Recent experiments with interacting trapped ion-atom mixtures have extensively studied ion cooling or heating through elastic ion-atom collisions. However, for homonuclear systems such as Rb-Rb^{+} or Na-Na^{+}, the sympathetic ion cooling could be due to (*i*) elastic collisions between the fast ion and an ultracold atom, resulting in a slow ion after collision, or (*ii*) resonant charge exchange between a fast ion and an ultracold atom, resulting in an ion essentially at rest, or a combination of both. It is difficult to distinguish the contribution of (*i*) and (*ii*) individually in an experiment and therefore the role of resonant charge exchange in the ion cooling process has eluded direct experimental verification.

During the past year, experimentalists at the Institute have developed a novel method of cooling ions that is based on resonant charge exchange (RCE) between the trapped ion and the ultracold parent atom. Specifically, cooling of trapped Cs^{+} ions by collisions with co-trapped, ultracold Cs atoms and, separately, by collisions with co-trapped, ultracold Rb atoms was demonstrated. It was observed that the cooling of Cs^{+} ions by Cs atoms is more efficient than cooling of Cs^{+} ions by Rb atoms. This signalled the presence of a cooling mechanism apart from the elastic ion-atom collision channel for the Cs–Cs^{+} case, which is cooling by RCE. The efficiency of cooling by RCE was determined experimentally and found to be higher than cooling by EC. This result will form the experimental basis for future studies on charge transport by hopping in atom-ion hybrid systems.
[Sourav Dutta and S. A. Rangwala]

Photodissociation of trapped $Rb2^{+}$: Implications for Simultaneous Trapping of Atoms and Molecular Ions

Research over the past year has been geared towards studying, both experimentally and theoretically, the direct photodissociation of trapped $^{85}Rb^{+}_{2}$ (rubidium) molecular ions by the cooling light from the ^{85}Rb magneto-optical trap (MOT). Vibrationally excited Rb^{+}_{2} ions were created by two photon ionization of Rb_2 molecules formed photoassociatively in the Rb MOT and were trapped in a Paul trap co-centric with the MOT. It was found that the trap lifetime of Rb^{+}_{2} ions is reduced to less than 500 ms in presence of the light used to laser cool the Rb atoms. This was attributed to direct photodissociation of Rb^{+}_{2} by a 780 nm photon that excites the Rb^{+}_{2} ion to a dissociating electronic state. The observed decay rate of the trapped Rb^{+}_{2} ion signal in the presence of the MOT cooling light was in agreement with calculated rates for Rb^{+}_{2} photodissociation. The results hint that simultaneous trapping of Rb atoms and Rb^{+}_{2} ions will be challenging. The photodissociation mechanism due to the MOT light is expected to be active and therefore universal for all homonuclear diatomic alkali metal molecular ions.
[S. Jyothi, Tridib Ray, Sourav Dutta, S. A. Rangwala, A. R. Allouche, Romain Vexiau and Olivier Dulieu]

Two-photon photoassociation of LiRb

Using two-photon photoassociation (PA) spectroscopy of ultracold heteronuclear LiRb molecules, RRI staff in collaboration with international peers have determined the binding energies of the loosely bound levels of the electronic ground singlet and the lowest triplet states of LiRb. Strong two-photon PA lines with power broadened linewidths greater than 20 GHz at relatively low laser intensity of 30 W/cm2 was observed. The implication of this observation on direct atom to molecule conversion using stimulated Raman adiabatic passage was studied. Theoretical analysis of the prospect for electronic ground-state molecule production was also carried out.
[Sourav Dutta, Jesús Pérez-Ríos, D. S. Elliott and Yong P. Chen]

Cavity QED related experiments

All-optical switching in a continuously operated and strongly coupled atom-cavity system

During the past year RRI staff have experimentally demonstrated collective strong coupling, optical bistability, and all-optical switching in a system consisting of ultracold ^{85}Rb atoms, trapped in a dark magneto-optical trap, and coupled to an optical Fabry-Perot cavity. The collective strong coupling was established by the observation of vacuum Rabi splitting (VRS) in the transmission spectrum of an on-axis weak probe beam. A closer look at VRS measurements done with different probe light intensities showed that VRS decreases with increasing probe intensity. The measurements also revealed an asymmetry in the line shape of the vacuum-Rabi peaks – a signature of optical bistability. When the probe laser is locked to the atomic transition and its power

scanned, the cavity transmission showed bistable behaviour and the cavity input-output curve showed hysteresis. The shape of the hysteresis could be controlled by another off-axis control laser tuned near a different atomic transition. This results from the probe and control beams forming a Λ-type system. It was also demonstrated that the cavity transmission can be switched on and off in micro-second timescales using micro-Watt control powers.
[Sourav Dutta and S. A. Rangwala]

Nondestructive detection of ions by atom-cavity collective strong coupling

During the past year, RRI staff demonstrated a technique, based on atoms coupled to an optical cavity, for nondestructive detection of trapped ions. They demonstrated the vacuum - Rabi splitting (VRS), arising from collective strong coupling of ultracold Rb atoms and a cavity, to change in the presence of trapped Rb^+ ions. The Rb^+ ions are optically dark and the Rb atoms were prepared in a dark magneto-optical trap. The VRS was measured on an optically open transition of the initially dark Rb atoms. The measurement is fast, nondestructive, and has sufficient fidelity to permit the measurement of the atomic-state-selective ion-atom collision rate. This demonstration illustrated a method based on atom-cavity coupling to measure two-particle interactions generically and nondestructively.
[Sourav Dutta and Sadiq Rangwala]

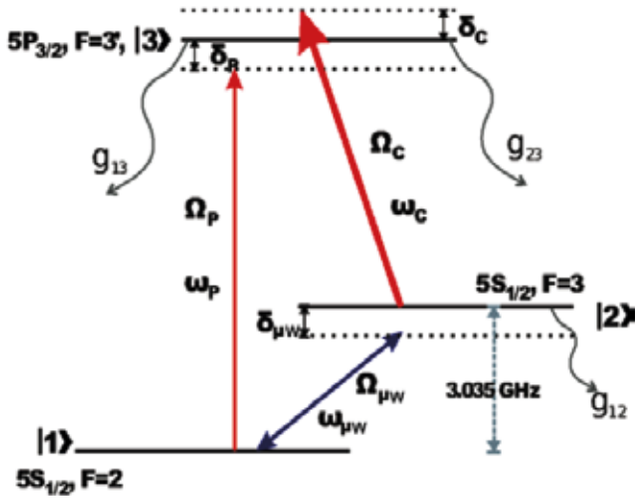
Lasing by driven atoms-cavity system in collective strong coupling regime

The interaction of laser cooled and trapped atoms with resonant light is limited by the linewidth of the excited state of the atom. Another precise optical oscillator is an optical Fabry-Perot cavity. The combining of cold atoms with optical oscillators is emerging as an area with great potential for precision measurements and the creation of versatile quantum optics systems.

Experiments conducted over the past year at the Institute showed that when driven atoms are in the collectively strongly coupled regime with the cavity, exhibiting vacuum Rabi splitting (VRS), lasing was observed for the emitted light, red detuned from atomic transition. This was demonstrated experimentally by the observation of a lasing threshold, polarisation purity, mode purity, and line narrowing. The laser was created spontaneously by the atomic emission into the cavity mode, which stimulates cavity emission, and is capable of operating continuously without a seed laser. The gain mechanism was understood by theoretical modeling and illustrated why the observed lasing is generic to the coupled system. Such studies open up a range of possibilities of using the phenomenon for a variety of new measurements.
[Rahul Sawant and S. A. Rangwala]

Signature of transfer of quantum correlations between microwave and optical fields with a closed level scheme: The noise correlation signatures

Research over the past 3-4 years have been towards experimentally studying a atom-light interaction scheme called the atomic Delta scheme shown in the figure. The aim of this study is to understand the transfer of superposition correlations created in the atomic hyperfine spin states to light and microwave electromagnetic (EM) fields which interact with the superposed atomic states. This study resulted in demonstrations of several interesting features which occur in the steady state regime of EM-waves- atomic-state interaction which were chronicled in earlier reports.



An atom-light interaction scheme called the atomic Delta scheme

Research during the past year has been geared towards gathering and mastering the requisite experimental tools to study transient temporal behaviour and change in noise power spectrum during both steady-state and transient regimes in this system. Towards this end several experimental signatures like study of noise features in transmitted intensity of a probe, auto-correlation of probe signal, cross-correlation of probe signal with that of the coupling field and similar features in the microwave field domain were identified. The necessary tools have been assembled with the help of local electronic technical support and real time experiments will be undertaken soon.
[Asha K., Ayyappan Jayaraman, Meena M.S. and Andal Narayanan]

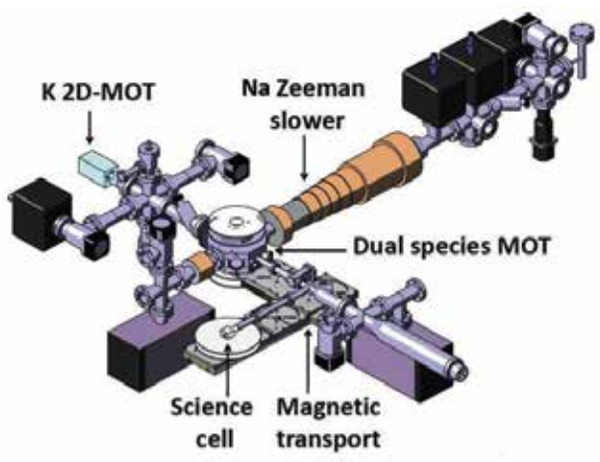
Quantum simulation of condensed matter physics using degenerate gases

Quantum Degenerate Mixture of Neutral Sodium and Potassium atoms

LAMP staff have continued their efforts during the past year

in setting up of a new experiment facility in the Raman Research Institute, towards creating a Sodium-Potassium gas mixture at nano-Kelvin temperature. At this very low temperature, well below critical temperature for bosonic species and fermi temperature of fermionic species, the behavior of the trapped cloud can be completely described by quantum theory and thermal fluctuations can be ignored. Therefore, the system can be an ideal test bed for investigating purely quantum mechanical phenomena and ideal for investigating complex condensed matter physics problems such as unconventional superconductivity and disordered-interacting phase diagram, to name a few.

As a long-term goal, the experiment will evolve to produce quantum degenerate ground state molecules with permanent electric dipole moment. These molecules can in turn be trapped in periodic potential created by interfering trapping light and the magnitude of the effective dipole moment can be manipulated using external electric fields. Therefore, effects of true long-range interactions in quantum gas can be investigated in this experimental system.
[Maheswar Swar, Sagar Sutradhar, Bhagyalakshmi D., Sanjukta Roy and Saptarishi Chaudhuri]



Schematic design of the quantum mixture experiment

Bose-Einstein condensate

Bose-Einstein condensation of Rubidium atoms

At ultra-low temperatures a cloud of bosonic atoms behave as a macroscopic matter wave. Moreover the inter-particle interaction in this macroscopic matter wave can be precisely controlled using external magnetic field. The Bose-Einstein condensate can be trapped in arbitrary external potentialincluding a disordered potential. Hence, disordered-interacting bosonic quantum matter can be investigated in such an experimental system. LAMP staff have during the year been upgrading one of the existing experimental facilities in LAMP group to produce a Bose-Einstein condensate (BEC).
[Hema Ramachandran, Sanjukta Roy, Bhagyalakshmi D., Maheswar Swar, Dhanalakshmi D. and Saptarishi Chaudhuri]

Light in Random Media

Real time imaging through fog

Numerous everyday situations like navigation, medical imaging and rescue operations require viewing through optically inhomogeneous media. This is a challenging task as photons propagate predominantly diffusively (rather than ballistically) due to random multiple scattering off the inhomogenieties. Real-time imaging with ballistic light under continuous-wave illumination is even more challenging due to the extremely weak signal, necessitating voluminous data-processing. Research over the past few years by LAMP group staff has eventuated into the ability to image through strongly scattering media in real-time and at rates several times the critical flicker frequency of the eye, so that motion is perceived as continuous. Two factors contributed to the speedup of more than three orders of magnitude over conventional techniques - the use of a simplified algorithm enabling processing of data on the fly, and the utilisation of task and data parallelization capabilities of typical desktop computers. The extreme simplicity of the technique, and its implementation with present day low-cost technology, holds promise for its utility in a variety of devices in maritime, aerospace, rail and road transport, in medical imaging and defence. It is of equal interest to the common man and adventure sportsperson like hikers, divers, mountaineers, who frequently encounter situations requiring realtime imaging through obscuring media. Research during the past year was geared towards realizing the commercial viability of the methodology by conducting experiments in real fog conditions in Kodaikanal.
[Sriram Sudarsanam, James Mathew, Swapnesh Panigrahi, Julien Fade, Mehdi Alouini, Meena and Hema Ramachandran]

Brain Computer Interface

Project CAPABLE aims at making Brain-Computer Interface systems that can be used to control and operate devices using brain signals alone, without any physical action. One such system, based on visually evoked potentials has been developed, with all components being made in-house. It has been integrated into a single, stand-alone, portable system. On the hardware side, it consists of electrodes, bio-amplifiers, digitisation and signal processing unit and action devices. On the software side it consists of the generation of visual stimuli, detection of visually evoked potentials, inference of

user selected action, and driving of devices. The protocols for evoking visual potentials and for identifying intent of action have been optimised, so as to obtain more than 99% accuracy. The system has been used to manipulate a robotic arm using brain signals.
[S. Sujatha, Rameshwara, B. Ramesh and Hema Ramachandran]

Intense Light Matter Field Interaction

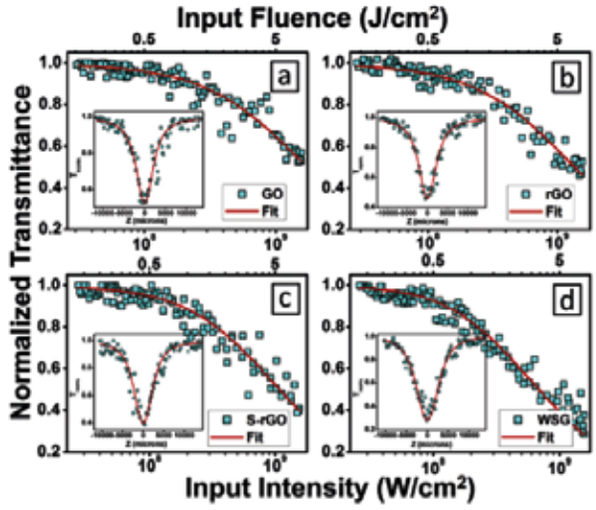
The optical response of a material scales linearly with respect to incident radiation. However, when the intensity of the incoming radiation (in other words the amplitude of the electric field) is sufficiently high the material can respond nonlinearly. The study of interaction of intense light with matter 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 a 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. A variety of materials were studied using short and ultrashort laser pulses, with the aim of investigating the nonlinear optical absorption properties in the nanosecond and femtosecond regime. In another work, laser ablation was used to optimize the surface structure of Si for enhanced ion and electron emission. Plasmas can be generated in the lab by the interaction of intense laser pulses with suitable targets. Such laser-produced plasmas have myriad applications, such as nanoparticle and nanocluster generation, second and high-order harmonic generation, UV and EUV generation, X-ray generation, and attosecond pulse generation. Research over the past year at the Institute was geared towards understanding the emission dynamics and properties of plasmas generated from Al, Cu and Zn targets.

Optical nonlinearity in nanostructured and other materials

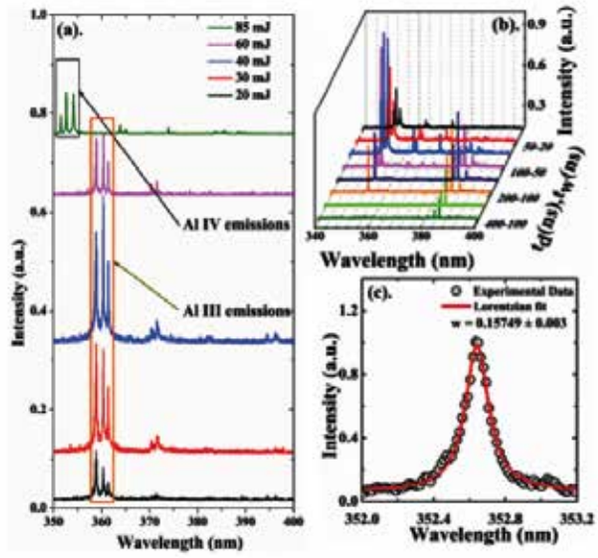
One aspect of research, during the year, was focused on studying nonlinear optical behaviour in a variety of nanostructured and other materials. Specifically, the nonlinear optical behavior of water soluble graphene, rGO-Ag hybrid nanoparticles, polymer-organic dye nanocomposites, $BaTiO_3$, Sb_2Se_3 and $MgFe_2O_4$ nanoparticles, and light emitting $Tb_2(MoO_4)_3$:Sm^{3+}/Eu^{3+} nanophosphors were investigated. Measurements were carried out using short (5 ns) and ultrashort (100 fs) laser pulses, to investigate the different temporal domains of optical nonlinearity.
[Nandakumar Kalarikkal, Reji Philip and collaborators]

Spectroscopic study of ultrafast laser-induced plasmas

Research over the past year investigated laser produced plasmas generated from Cu, Aluminum and Zinc targets. Emission dynamics was studied as a function of laser fluence [Anoop et.al., J. Appl. Phys. 120, 185901 (2016)], the effect of ambient pressure on Stark broadening of emission lines was investigated [Rao et.al., Phys. Plasm. 23, 043503 (2016)], and optimization of the generation of highly ionized species from an Al plasma was carried out [Smijesh et.al., Phys. Plasm. 23, 113104 (2016)].



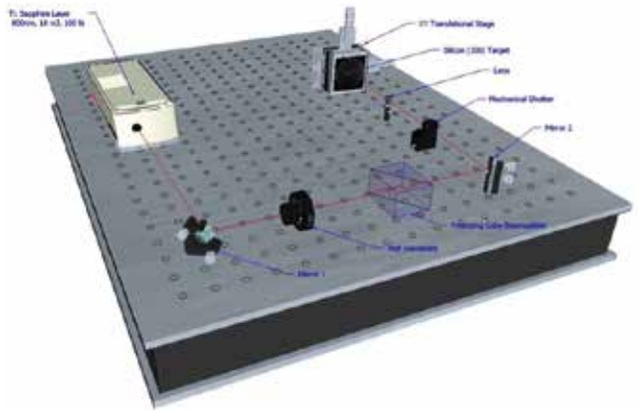
Efficient optical limiting measured in isolated, sparingly sulfonated, water soluble graphene. The nonlinearity has different magnitudes in the nanosecond and femtosecond excitation domains [S. Perumbilavil, K. Sridharan, D. Koushik, P. Sankar, V.P.M. Pillai, and R. Philip, Carbon 111, 283 (2017)].



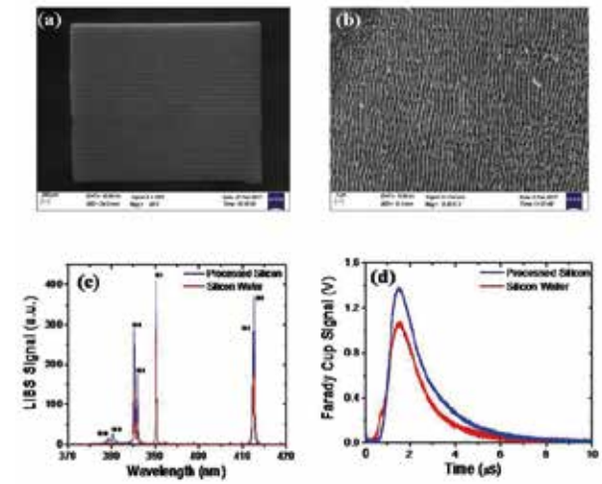
Spectrum of a laser produced Aluminum plasma, which is optimized for maximum Al3+ emission [N. Smijesh, K.H. Rao, N. Klemke, R. Philip, I.V. Litvinyuk and R.T. Sang, Phys. Plasm. 23, 113104 (2016)].

Enhanced Optical and Ion emissions from Nanostructured Silicon Target

Laser induced periodic surface structuring (LIPSS) is a powerful technique for modifying the surface properties of solid targets. Nanoscale order LIPSS on a silicon (100) target using femtosecond Ti:Sapphire laser (800nm, 100 fs, 10 mJ, 10 Hz) pulses was carried out. The obtained periodic structures were strongly dependent on the laser pulse energy, polarization, and number of shots delivered on the target. An area of 5x4 mm^2 was periodically surface structured employing p-polarized laser shots, using 100 μJ energy per pulse. The processed surface showed a substantial reduction in the reflection of incident laser light with respect to unprocessed silicon. The processed silicon surface was used as a target for Laser induced breakdown spectroscopy (LIBS)



Schematic of the femtosecond laser induced surface structuring process in atmospheric condition. The structuring in different ambient conditions was performed by keeping the target and XY translational stage in a high vacuum chamber.



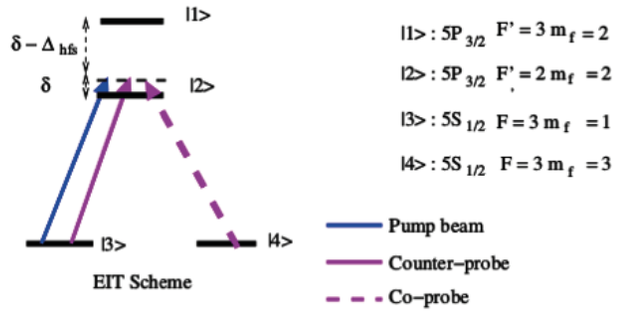
(a) Femtosecond laser induced periodic surface structures on the silicon target. (b) Zoomed view of (a). (c) & (d) show the relative enhancement seen in the LIBS spectra and Faraday Cup signals from the processed silicon surface. Blue colour represents the signal from processed silicon whereas red represents the signal from the unprocessed silicon wafer.

and Faraday Cup (FC) measurements, to investigate the increased coupling of laser energy on to the material. An enhancement factor of ≈ 1.5 was measured in both LIBS and FC signals, which confirmed that LIPSS is a versatile method for enhancing the coupling of laser energy to a solid target. The enhancement in energy coupling resulted in increased optical and ion emissions from the laser ablation process.
[Anoop K. K. Reji Philip, S.S. Harilal, M.P.Polek, Salvatore Amorsuo and Riccardo Bruzzese]

Precision Atom-Light Spectroscopy

Interacting multiple superposition states of light and atom: Temporal studies

During the past year LAMP staff have set up a new experiment to study the dynamics of competing multiple superposition states. The aim of this study was to identify control parameters, which decide the final form of the resultant superposition state when two or more superposition states interact. Interacting superposition states are first formed with atom and light variables using electromagnetically induced transparency with a level scheme called the double-Lambda level scheme shown below. Initial experimental results indicate that saturation of levels play an important role in steady state non-linear response of an optical probe field in such systems.
[Adwaith K.V., Sayali Shevate and Andal Narayanan]



Electromagnetically induced scheme called as the double –Lambda level scheme

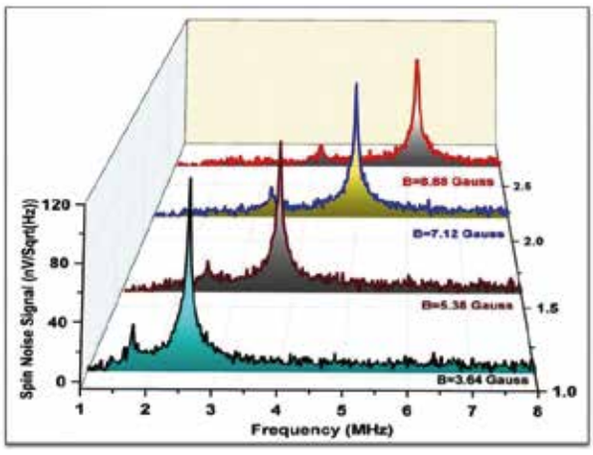
Non-Markovian signatures in atom-light interaction

LAMP group members continued thier study of non-Markovian processes in atom-light interaction where environmental correlations persist on time-scales comparable to or exceeding system time-scales. In this regime, the state of the environment decides the short-term dynamics and the system may never settle to a steady state. The effect of such long-lived environmental correlations on transport processes within the system was studied. The theoretical analysis of a non-Markovian interaction of an proto-typical atomic V

system with a thermal and vacuum EM field bath has begun yielding results.
[Ayyappan Jayaraman, Atul V and Andal Narayanan]
Spin noise spectroscopy of neutral thermal Rubidium atoms

Non-perturbative detection of true many body states are of fundamental importance especially in condensed matter physics and quantum optics. Recently, there is renewed interest in non-perturbative measurement of ultra-cold atoms via polarization rotation measurements. However, the fluctuations in the rotation of polarization reveals further dynamic quantities relevant to the system under investigation.

In order to develop and understand such a non-perturbative detection scheme, LAMP staff performed experiments on spin fluctuations in a thermal vapor investigated by the probe beam polarization fluctuation measurements. Such fluctuations in far-detuned probe laser passing through a thermal vapor in presence of an orthogonal magnetic field revealed intrinsic spin fluctuations in the system. This technique has promising applications in many other similar systems such as ultra-cold quantum gases. A polarization sensitive precision detection technique has been developed in the laboratory and spectrum of polarization fluctuation is measured and interpreted as intrinsic spin noise from thermal atomic vapor.
[Maheswar Swar, Dibyendu Roy, Hema Ramachandran, Sanjukta Roy and Saptarishi Chaudhuri]



Spin noise signal recorded from thermal atomic vapor at various perpendicular magnetic fields

Quantum Information, Computing and Communication

During the past few years RRI has accumulated infrastructural capability and intellectual knowhow to conduct cutting edge research in the fields of quantum information, quantum computing and quantum communication using quantum optics based tools. It is worth pointing out that the Institute has pioneered the manufacture and applications of single, heralded and entangled photon sources in India which were hitherto unexplored in our country.
Any truly quantum application of light requires harnessing it at a single particle (photon) level and this requires dedicated resources and technology to materialize, which has been established at the Institute.
Nobel laureate Richard Feynman famously said in 1955 "No one understands quantum mechanics", it is indeed true that while a lot has been understood over the last several decades and all such knowledge gained has in fact given us marvelous technology and innovations, there is a lot that is still left to be understood in the working of quantum physics. For instance, the holy grail of theoretical physicists over the last several decades has been working towards a unified theory of quantum mechanics and General Relativity. Efforts are on but we do not yet have a unified theory of quantum gravity. One of the approaches towards this unification has been in generalizing quantum mechanics principles with a hope that the generalized version will have a scope of overlap with General Relativity. Incidentally, this is one of the major thrust areas of research in the Theoretical Physics group at our Institute (More details in the TP section of this Annual Report).

Thus one of the main themes of research is precision tests of the laws of quantum mechanics. Putting bounds on various physical principles and postulates is of paramount importance especially in the quest towards quantum gravity. A true understanding of the limitations and limits of these principles will provide the theorists practical bounds within which to place their theory rather than ideal constructs. Towards this aim, research has been geared towards studying both theoretically and experimentally the common application of the superposition principle in interference experiments. Theory work published recently proved that this naïve application needs to be corrected. This has been substantiated with experiments conducted in the past year, which gave the first ever fool-proof measurement of a non-zero Sorkin parameter, which was in fact non-zero due to the correct application of the superposition principle.

Another research theme of particular interest for both fundamental science as well as technological applications - for example, secure communication - is the Institute's work in the field of experimental quantum key distribution. Another main theme of research being pursued is in the fields of quantum information and quantum measurements. In quantum information, focus is towards studying different forms of quantum correlations.

The last but definitely not the least broad theme of research is

in the field of quantum computation, especially harnessing higher dimensional quantum systems. Research over the last few years has been on investigating a system of qutrits formed using the spatial degree of freedom of the single photon. The architecture is being investigated both theoretically as well as through experiments. A more detailed description of the research in the above mentioned topics undertaken during 2016-17 follows.

Quantum Information

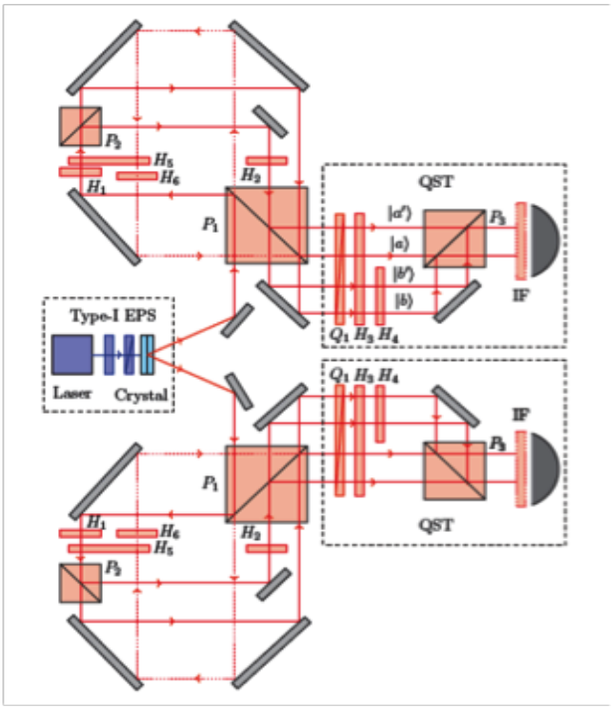
During the past year, LAMP members accomplished two pieces of work in the general area of quantum information. One was an experimental proposal for manipulation of a phenomenon called Entanglement Sudden Death, which has been published in Journal of Optical Society of America B. The second was an appraisal on a very interesting phenomenon in quantum measurements called the Quantum Cheshire Cat effect. There is also a third piece of work, which is an experiment on higher dimensional quantum systems and is described under the theme Quantum Computation as it is slightly more relevant to that theme than quantum information although it can be classified under both.

Manipulation of entanglement sudden death in an all optical set up

The phenomenon of Entanglement Sudden death in an all-optical set-up was investigated. Entanglement is a quantum correlation, which serves as a resource in several quantum information, computation and communication protocols. However, when entangled systems interact with their environment, it can lead to degradation of the entanglement and in some situations the entanglement can disappear completely at a finite time. If this happens, then the correlation is not available any more for quantum operations. Staff at the Institute has proposed a way of holding on to the entanglement for longer so that useful operations may be performed with more time available in hand. The investigations led to an experimental proposal using an all-optical experimental set up which is, over the last year, being set up in the laboratory at the Institute.

The unavoidable and irreversible interaction between an entangled quantum system and its environment causes decoherence of the individual qubits as well as degradation of the entanglement between them. Entanglement sudden death (ESD) is the phenomenon wherein disentanglement happens in finite time even when individual qubits decohere only asymptotically in time due to noise. Prolonging the entanglement is essential for the practical realization of entanglement-based quantum information and computation protocols. For this purpose, the local NOT operation in the computational basis on one or both qubits has been proposed. This work formulated an all-optical experimental set-up involving such NOT operations that can hasten, delay, or completely avert ESD, all depending on when it is applied during the process of decoherence. Analytical expressions for these were derived in terms of parameters of the initial state's density matrix, whether for pure or mixed entangled states. During the past year the schematics of the experiment was studied. Detailed theoretically analysis of the problem was carried out along with simulations of such manipulations of ESD.

[A.Singh, S.Pradyumna, A.R.P Rau and U.Sinha]



Proposed experimental setup for manipulation of entanglement sudden death

Appraisal of the Quantum Cheshire Cat effect

This work, done at RRI during the last year, was an appraisal of the phenomenon called the Quantum Cheshire Cat effect with the aim of exploring both theoretical understanding of the effect as well as experimental status. To set the stage for what was done, one could imagine going back to Lewis Carol's famous piece of work called Alice in Wonderland. While following Alice's adventures in her wonderland, one comes across a smiling cat; the smile lingers on while the cat disappears. This is the iconic Cheshire cat from fairly-tale folklore. However, this grin without the cat and cat without the grin also forms the basis for a quantum phenomenon, through which using the concept of weak measurements, one can separate the physical location of a particle from one of its properties. This is the Quantum Cheshire Cat effect. Ever since its theoretical inception and one experimental attempt, this has been a controversial effect simply because people find it difficult to believe that such a thing can be possible.

The Quantum Cheshire Cat [New J. Phys. 15, 113015, 2013] (QCC) is an effect defined within the Weak Measurements framework by which a property of a quantum particle appears to be spatially separated from its position. The status of this effect has however remained unclear, as claims of experimental observation of the QCC have been disputed by strong criticism of the experimental as well as the theoretical aspects of the effect.

Recent work by LAMP staff has clarified in what precise sense QCC can be regarded as an unambiguous consequence of the standard quantum mechanical formalism applied to describe quantum pointers weakly coupled to a system. In light of this clarification, the raised criticisms of QCC effect were rebutted. It was further shown that the limitations of the experiments performed to date imply that a loophole-free experimental demonstration of QCC has not yet been achieved.
[Q.Duprey, S.Kanjilal, U.Sinha, D.Home and A.Matzkin]

Quantum Entanglement with ultra-cold Rydberg atoms

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

Control and manipulation of ultra-cold Rydberg atoms offer a promising avenue for quantum information processing. Rydberg states are highly excited atomic states with a large principal quantum number n near the ionization threshold. Atoms in Rydberg states exhibit interesting characteristic features such as large dipole moments. For example, Rydberg states with a principal quantum number n ~ 50 has a dipole moment few thousand times that of water molecule. This makes the Rydberg atoms highly polarizable with static polarizability scaling as n^7 and hence very sensitive to DC or AC electric fields. Such large dipole moment possessed by Rydberg atoms gives rise to large interaction between them via dipole-dipole coupling which scales as $1/R^3$ where R is the inter-atomic distance. The interaction energy between two Rydberg atoms exhibit a strong dependence on the principal quantum number n and can be tuned from the Van der Waals regime to the $1/R^3$ regime by using an electric field or by varying the inter-atomic distance. Rydberg interactions between ultra-cold Rydberg atoms can enable the generation of entangled states and lead to Quantum information processing via realization of fast quantum gates. The generation of quantum entanglement and the realization of Quantum gate with two single Rydberg atoms has been achieved elsewhere. However, for the purpose of scalability of Quantum information processing, it is desirable to realize mesoscopic entanglement with a large number of atoms.
The objective of this experiment is the generation of mesoscopic entanglement using Rydberg blockade mechanism. The proposal is to create mesoscopic entanglement in an ensemble of ultra-cold atoms with a single control atom. The entanglement can be implemented in a single step with high fidelity within a time-scale of one microsecond by combining long-range Rydberg interactions with the quantum interference phenomena of Electromagnetically Induced Transparency (EIT). This would eliminate the need for individual addressing of the ensemble of atoms and hence would enable the realization of a fast mesoscopic quantum gate.

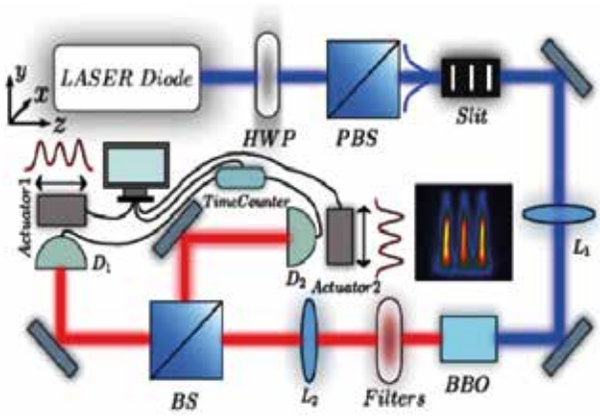
In this direction, the following work has been accomplished during the past year:
A. Complete automation of the experiment: All the relevant instruments needing precise timing control during the experiment have been connected to the computer automation system and can now be accurately controlled using NI-PCI cards and Labview programming. A comprehensive Labview program, which can control all the relevant aspects of the experiment, has been written.
B. Realization of a microscopic optical dipole trap for single atom trapping: The precise alignment of the trapping laser beam at the center of the cold atomic cloud for the realization of a microscopic optical dipole trap for single atom trapping is in progress.
C. Measurement of the micron-sized focal spot of the trapping beam using interferometric technique: To ensure that only a single atom is trapped in the microscopic optical dipole trap, the focal spot of the trapping beam at the cold atom reservoir should be ~ 1 micron so that the trapped atoms are in collisional blockade regime which prevents the occurrence of more than one atom in the trap. The experimental set-up for the measurement of the focal spot of the trapping beam was realized.
D. Procurement of the tunable frequency doubled diode laser for Rydberg excitations: A detailed calculation was done to finalize the specific Rydberg levels to be addressed in the experiment to realize mesoscopic entanglement with Rydberg atoms. Thereby, the range of wavelength and all the relevant options required for the laser was finalized. The state-of-the-art tunable frequency doubled diode laser will be delivered soon. The frequency doubling (SHG) stage of the laser is a folded ring cavity in bow-tie configuration with excellent thermal and mechanical stability.
E. Detailed planning and design of a new generation of single atom experiment: A new generation of experiment is being planned and designed where a glass cell will be used instead of the currently used steel vacuum chamber so that the High

numerical aperture lenses for realizing the microscopic dipole trap can be placed outside the vacuum glass cell offering much improved flexibility and controllability to the experiment. In this direction, a new set of anti-Helmholtz coils has been designed and built and the complete design of the mounts holding a pair of anti-Helmholtz coils, three pairs of compensation coils and two High NA lens mounts is in progress.
[Sanjyukta Roy and Hema Ramachandran]

Quantum Computation and Communication

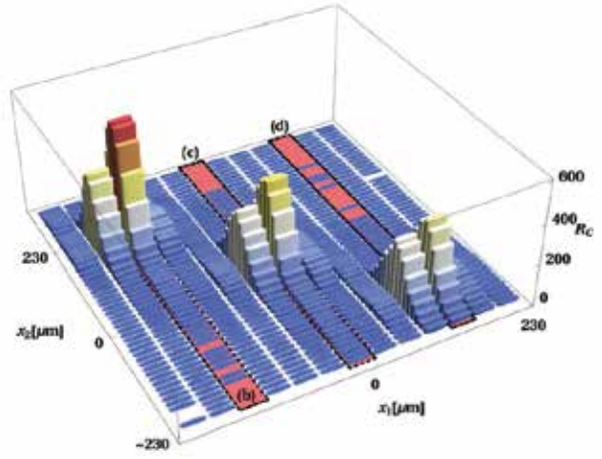
Correlated photonic qutrit pairs for quantum information and communication

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



Schematic of the experimental set-up. Horizontal pump beam is directed to be incident on a triple slit aperture. Lens L1 is used to transfer the image of the pump beam on the Type I BBO crystal. After appropriate filtering of the blue pump beam, another lens L2 is used to transfer the signal and idler spatial profiles to actuated detectors placed on either side of a beam splitter. The spatial profiles of the signal and idler photons are measured using detectors D1 and D2 and the spatial correlation is measured using an appropriate coincidence logic unit.

LAMP staff are exploring a qudit architecture based on spatial degree of freedom of a single photon. Higher dimensional quantum systems have a very important role to play in quantum information, computation as well as communication. In photonic systems, it is common to use the photon's polarization degree of freedom for various investigations. However, this restricts us to only two orthogonal states, hence qubits for manipulation. In a recent work, LAMP staff had theoretically analyzed and experimentally demonstrated a system of two photonic qutrits, which are correlated in the spatial degree of freedom. The qutrits have been generated by modulating the pump beam in a spontaneous parametric down conversion process using an aperture based system. In principle, this system can be scaled up to generation of even higher dimensional correlated qudits with possible application for quantum communication and computation implementations. Quantification of the spatial correlations between a pair of qutrits can in principle also have applications in quantum communication whereby now one can explore a different degree of freedom i.e. spatial compared to the more conventional polarization degree of freedom.
[D.Ghosh, S.Bhar, T.Jennewein, P.Kolenderski and U.Sinha]



Coincidence counts, R_C measured as a function of position of detectors D1 and D2. The correlation was quantified in terms of the Pearson correlation coefficient. A very high correlation of 90 % has been obtained between the signal and idler photons in terms of their spatial correlation.

Fundamental tests of quantum mechanics

Measuring the deviation from the superposition principle in interference experiments

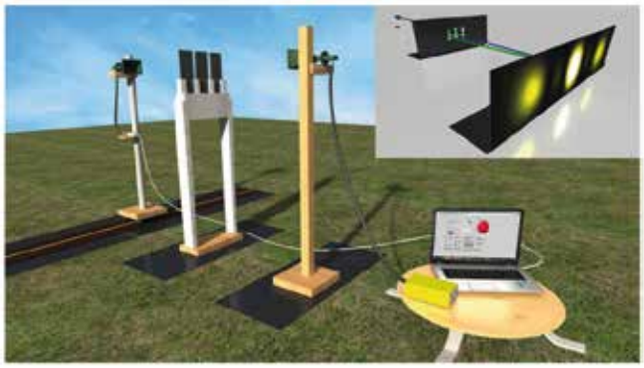
One major experimental achievement this past year has been the successful first measurement of a non-zero Sorkin parameter. Previous years annual reports had reported on theory work done by LAMP members which have been published in prestigious journals like Physical Review Letters and Scientific Reports where it was shown that the superposition principle is usually incorrectly applied in slit-based interference experiments when the sum of solutions for two slits opened individually is taken to be the solution for both slits opened simultaneously. These indicate different

boundary conditions and should be treated as such. In previous theory work, this correction had been quantified in terms of what is called the Sorkin parameter in literature and it was shown that the Sorkin parameter turns out to be non-zero only when the boundary conditions are correctly applied. This work was equally applicable to quantum mechanics as well as classical electromagnetism as this is a boundary value problem thus making it applicable to all situations where boundary conditions are incorrectly applied.

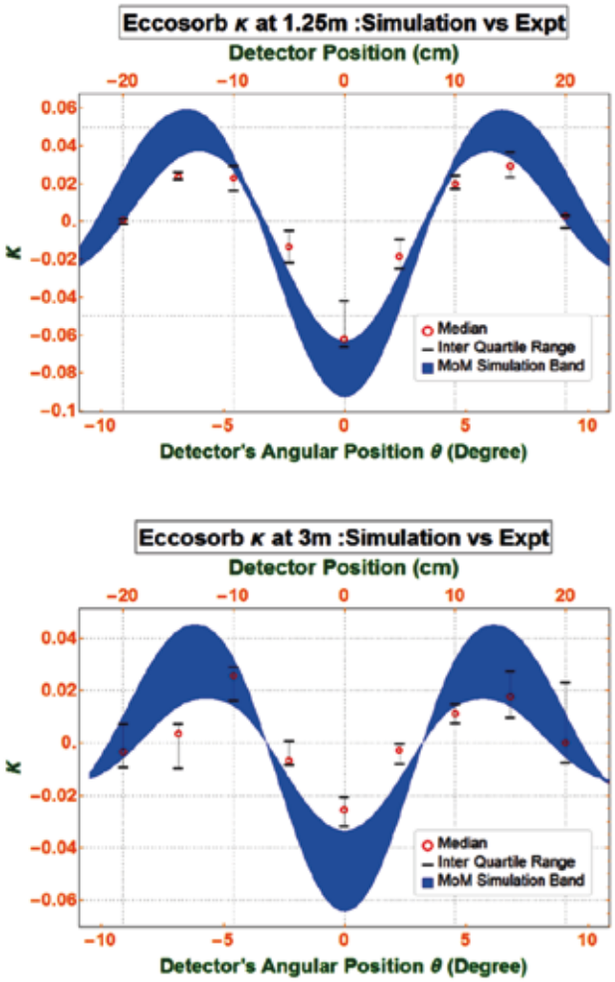
In 2014, experiments were undertaken to measure the non-zero Sorkin parameter. Making use of earlier findings, that this parameter can be experimentally measured especially if the experiment is done in long wavelength conditions, LAMP staff embarked upon an experiment using GHz frequency radiation from a horn antenna as a source and another horn antenna as a detector. This was exploring new grounds for the group at various levels as it involved using tools and equipment, which is more commonly used in radio astronomy research. Discussions with radio astronomy colleagues at RRI proved very helpful in this work.

During the past year LAMP staff took the first measurement of a deviation from the superposition principle in the microwave domain using antennas as sources and detectors of the electromagnetic waves. This deviation was quantified through the Sorkin parameter, which can be as big as 5% in this particular experiment. It was also shown that these results could have potential applications in formulating better error models in observational radio astronomy where similar assumptions are sometimes made about the application of the superposition principle.

Being the first reported non-zero measurement of the Sorkin parameter, this experiment is expected to have ramifications not only in quantum mechanics but also in seemingly unrelated areas of optics like precision cosmology. It will also change the base from zero to a non-zero value for the Sorkin parameter in the quantum measure theory approaches to generalizations of quantum mechanics.
[G.Rengaraj, U.Prathwiraj, S.N.Sahoo, R.Somshekhar and U.Sinha]

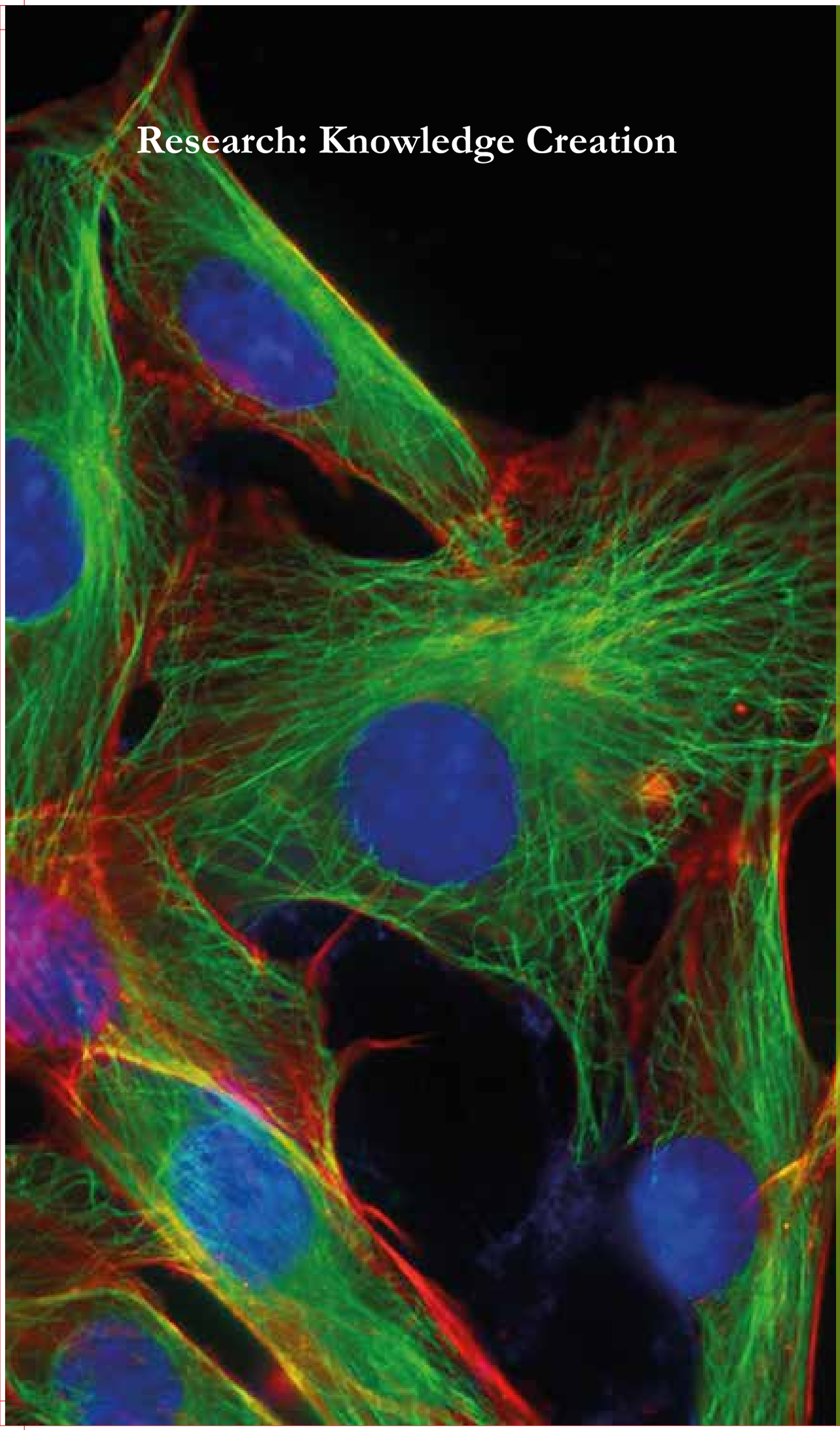


Schematic of the experimental setup



The plot on top is for source-slot plane distance of 1.25 m. The bottom plot is for source-slot plane distance of 3 m. Slot plane - detector plane distance is kept 1.25 m in both cases. As can be seen, experiment and theory match very well in both cases. Theory predicts a drop in the normalized Sorkin parameter values with increasing source-slot distance which is corroborated by experiment. As distance increases, the noise remains similar but signal drops making signal to noise go down which results in generally bigger error bars at larger distance.

Research: Knowledge Creation



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 2016-17

Aging and soft glassy rheology

Understanding the emergence of solidity (fluid to solid transitions) in soft materials is an important area of research since we encounter this behavior in our day-to-day life. Shaving foam, paint and toothpaste are examples of soft materials. Depending on the particle size there are two ways such transitions may occur: (i) by a reduction in the temperature of the system (glass transition), (ii) by increasing the density of particles (jamming transition), and (iii) by removing shear from the system. Owing to the myriad practical applications of such systems, detailed studies on these transitions are highly desired. Experiments were performed at RRI to understand the role of fragility (a measure of rate of change in system relaxation time with temperature or particle density) as a function of polydispersity in suspensions of soft colloidal particles approaching the jamming transitions. Such studies have potential applications in systems requiring solid to fluid transitions.

Naturally occurring soil is a mixture in which fine sand, colloidal clay and salt (minerals) are the major components. The structure of soil and hence its behavior is heavily dependent on the relative concentrations of the constituents. For example, soil acidity is known to be a limiting factor in plant growth thus playing a direct role in dictating agricultural yield and economy of a country. On the other hand, salinity of soil can explain various geophysical phenomena such as landslides and river delta formation. Thus, from a practical viewpoint, a fundamental understanding of the effect of relative concentrations of salt and acid on the structure-property relationship of soil is highly desired as this could pave the way towards increasing crop yield as well as disaster management. Surprisingly, a comprehensive study that sheds light on the structure and properties of colloidal clay as a function of salt and acid concentrations has been distinctly lacking.

Research during the past year by SCM researchers at RRI have addressed this with a set of experiments in which they monitored the stability of suspensions of acid and salt induced clay in water. Studies were also undertaken to understand the effects of dynamic heterogeneities in aging colloidal suspensions and interfacial instabilities between two fluids. A detailed description of the research undertaken at RRI during 2016-17 on these topics is given below.

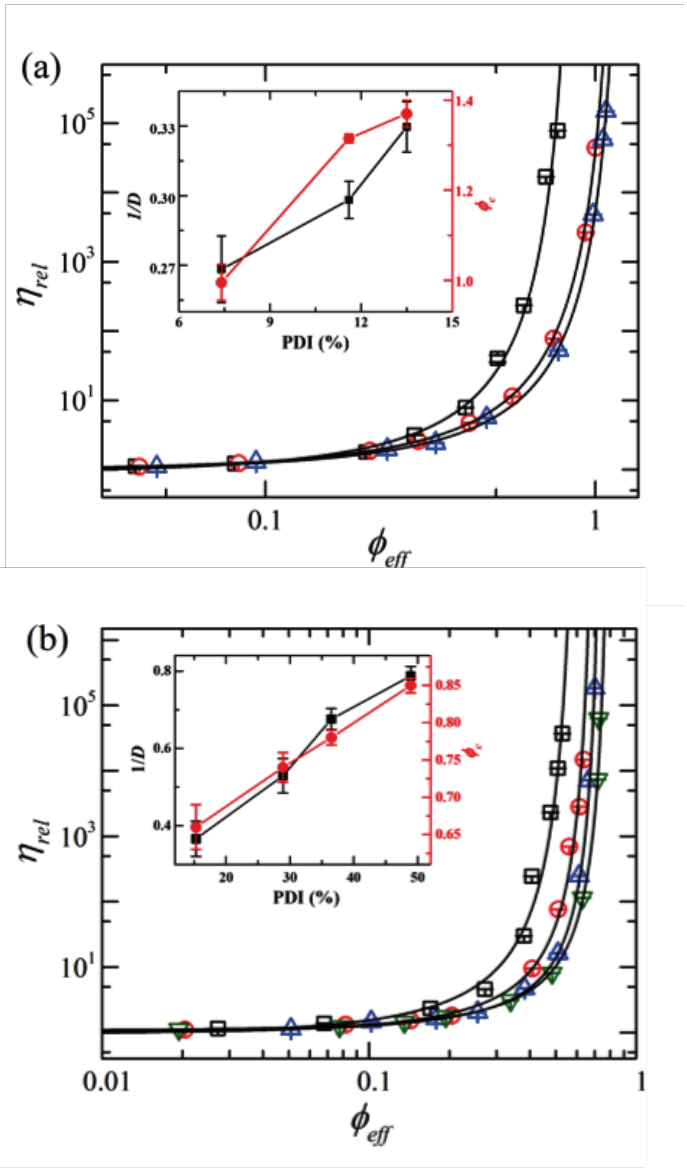
Study of the colloidal glass transition in suspensions of highly polydisperse poly(N- isopropylacrylamide) particles

During the past year experiments were performed at the Institute to understand the role of fragility and jamming volume fraction in suspensions of soft colloidal particles approaching the jamming transition. Particles synthesized in-house were characterized using dynamic light scattering (DLS) and field effect scanning electron microscopy (FESEM). Viscosity measurements were made to quantify their divergence with increasing volume fractions. The fragility changes obtained in these experiments were confirmed by performing Fourier transform oscillatory rheology experiments.

Thermoresponsive poly(N-isopropylacrylamide) (PNIPAM) particles of a constant swelling ratio and with polydispersity indices (PDIs) varying over a wide range (7.4%-48.9%) were synthesized in house to study the effects of polydispersity on the dynamics of soft PNIPAM colloidal systems. The zero shear viscosities of these colloidal suspensions, estimated from rheometric experiments, increased with increase in effective volume fraction and eventually diverged at a critical volume fraction. The data showed good agreement to the Vogel-Fulcher-Tammann equation, which is often used in the context of supercooled liquids. It was observed that increasing PDIs resulted in increasingly fragile supercooled liquid-like behavior, with the volume fraction for viscosity divergence also increasing monotonically. The increase in fragility was attributed to the prevalence of dynamical heterogeneities (DHs) in these polydisperse systems, while the simultaneous increase in the volume fraction characterizing the viscosity difference can be ascribed to the decoupling of the dynamics of the smallest and largest particles. Investigations of the effects of polydispersity on the intrinsic nonlinearity of soft PNIPAM particle suspensions at the third harmonic near the effective volume fraction for viscosity divergence showed that the intrinsic nonlinearity of these suspensions increases with

the increase in PDIs. These results are in agreement with theoretical predictions and simulations for polydisperse hard sphere colloidal glasses and clearly demonstrate that jammed suspensions of colloidal particles can be effectively fluidized with increase in particle PDIs. Suspensions of these particles are, therefore, excellent candidates for detailed experimental studies of the effects of polydispersity on the dynamics of glass formation.

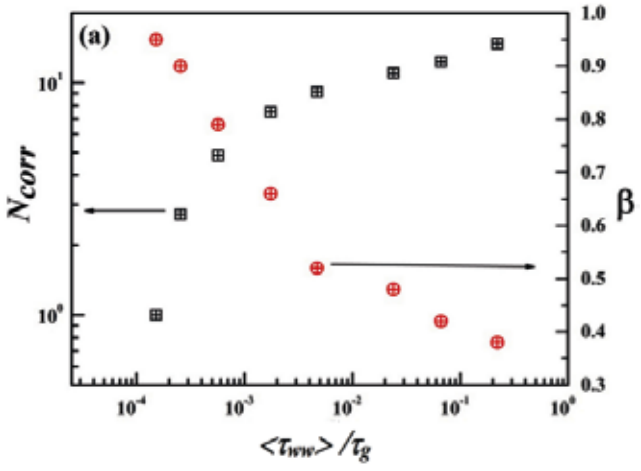
[Sanjay Behera, Paramesh Gadige, Debasish Saha and Ranjini Bandopadhyay]



The evolution of the relative viscosity of PNIPAM suspensions with increasing effective volume fractions is shown for several aqueous suspensions constituted by PNIPAM particles of different average particle sizes and size polydispersities. The suspensions were prepared using the one pot and semi batch techniques (left and right panels respectively). The fits of the data to the Vogel Fulcher Tammann equation (VFT) are shown by solid lines. The insets shows the fitting parameters: fragility (1/D – black squares) and the critical volume fraction phi_c at which the viscosity shows an apparent divergence (red circles)

Study of dynamical heterogeneities in aging colloidal nanoclay suspensions

An aqueous suspension of the synthetic clay Laponite can undergo a transition from a liquid-like ergodic state to a glass-like nonergodic arrested state. In an observation that closely resembles the dynamical slowdown observed in supercooled liquids subjected to a rapid temperature quench, the phenomenon of kinetic arrest in Laponite suspensions is accompanied by a growth in the α-relaxation or structural relaxation time with increasing sample aging time, t_w. The ubiquitous dynamic slowdown and fragility observed in glass forming liquids approaching the glass transition is typically ascribed to the heterogeneous dynamics and the growth in the size of distinct dynamical heterogeneities. Research during the past year has been on characterizing the dynamical heterogeneities in aging colloidal Laponite clay systems by invoking the three-point dynamic susceptibility formalism.



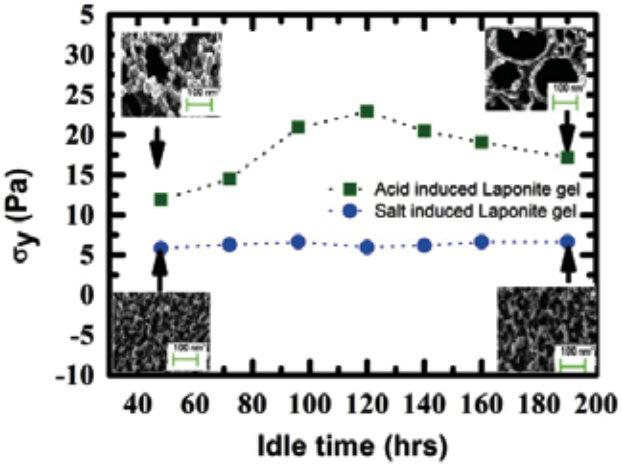
Plot of the average size of the dynamical heterogeneities N_{corr} (black symbols) and the stretching exponent β (red symbols) vs. <τ_{ww} >/τ_{g} for a Laponite concentration C_{L}= 3.0 wt.% . Here < τ_{ww} >/τ_{g} is the ratio of the average slow (alpha) relaxation time and the glass transition time of the colloidal suspension. N_{corr} shows a monotonic increase, with the initial rapid increase slowing down considerably at high < τ_{ww} > /τ _{g} while β shows a monotonic decrease.

Dynamical heterogeneities in colloidal glasses of soft, anisotropic Laponite particles have not been quantified in the literature. In an effort to study the approach of aqueous colloidal suspensions of Laponite as they approach dynamical arrest, researchers at the Institute probed the average time-dependent two-point intensity autocorrelation and its sensitivity to the control parameter t_w using dynamic light scattering experiments. It was shown that the distribution of relaxation time scales deduced from the Kohlrausch-Williams-Watts equation widens with increasing t_w signifying the heterogeneous dynamic slowdown. The three-point correlation function was obtained by taking the derivative of the decaying two-point correlation functions with respect to t_w .The calculated three-point dynamic

susceptibility exhibited a peak whose height increased with evolving t_w. The number of dynamically correlated particles, deduced from the peak-height, was seen to initially increase with t_w at a fast rate, before eventually slowing down close to the glass transition point. This observation is in agreement with published reports on supercooled liquids. Through this study, the presence and growth of dynamical heterogeneities in soft glassy suspensions of Laponite was confirmed, thereby shedding new light on the fragile supercooled liquid-like dynamics of aging suspensions of these anisotropic, charged, colloidal clay nanoparticles.
[Paramesh Gadige, Sanjay Behera, Debasish Saha and Ranjini Bandopadhyay]

Effect of aging on the yielding behavior of acid and salt induced Laponite gels

Rheological experiments were undertaken to study the mechanical properties of Laponite gels when prepared by adding sulfuric acid (H_2SO_4) and common salt (NaCl). A better understanding of the structure-property relationships of these gels was obtained by correlating cryogenic scanning electron microscopy images of the gel morphologies with the acquired rheological data.

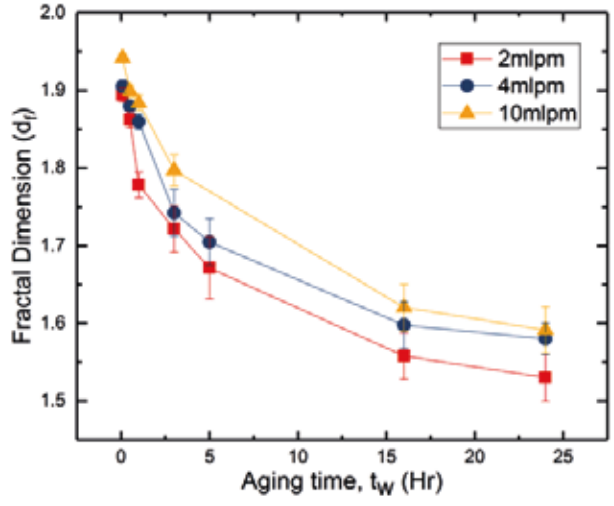


The yield stress of acid induced clay gels varies monotonically with sample idle time because of the evolution of the microstructure of the samples (Cryo-SEM images in the top insets). No such change in yield stress is observed in salt-induced clay gels as the sample microstructure does not change appreciably with idle time (Cryo-SEM images in the bottom insets).

The synthetic clay Laponite, when dispersed in water, shows rich phase behavior that depends on both clay and ionic concentrations. The flow properties of this clay dispersion can be tuned by incorporating different additives such as acid and salt. Experiments performed during the past year revealed that the acid induced Laponite gels form a visco-elastic solid with increasing idle time, while the salt induced Laponite gel transforms to a soft solid almost immediately after sample preparation. Furthermore, in the acid induced Laponite gels, a non-monotonic evolution of yield stress with idle time was observed. No such observation was evident for the salt induced Laponite gels. These observations are connected to the underlying morphology of the sample, which is governed by the osmotic pressure driven aging behavior of the suspensions. The aging dynamics and the subsequent structural evolution of the sample were further verified by performing a UV-Vis spectroscopy study and found to be in agreement with the rheological and Cryo-SEM experiments.
[Venketesh T Ranganathan, Ranjini Bandopadhyay]

Instabilities at the interface between a Newtonian fluid and an aging non-Newtonian fluid in a quasi two-dimensional geometry

The instability between a Newtonian and non-Newtonian fluid, confined between two parallel closely separated plates, is called Saffman Taylor (ST) instability, and results in the formation of wave like projections known as Saffman-Taylor "fingers". During the past year, SCM research studied the instabilities at the interface between two fluids, one of which is aging and non-Newtonian (an aqueous Laponite suspension) and the second i) CCl_4 which is immiscible in the Laponite suspension and ii) water which is miscible in the Laponite suspension.



The dependence of the fractal dimensions of the interfacial pattern that form when aging Laponite suspensions are displaced by water at different flow rates in a Hele-Shaw cell at gap size of 0.17 mm is plotted versus the suspension waiting time.

Specific focus was on understanding the physics behind pattern formation at the quasi–two dimensional interface between a Newtonian fluid (water and carbon tetrachloride), and an aging non Newtonian fluid (an aqueous suspension of Laponite (synthetic clay)) in a Hele-Shaw geometry. It was observed that the fractal dimensions of these patterns decreased with the aging time of the Laponite suspensions.

Soft materials such as aging Laponite suspensions may flow like a fluid or fracture as a solid due the application of mechanical stress. Observations showed that crack propagation of fingers occurred at high waiting times, when the Laponite suspension is displaced by water (a miscible fluid). Crack propagation patterns were, however, not observed when Laponite was displaced by an immiscible fluid (carbon tetrachloride) due to the presence of surface tension. [Janet Joy, Vipin Agrawal, Debasish Saha and Ranjini Bandyopadhyay]

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.

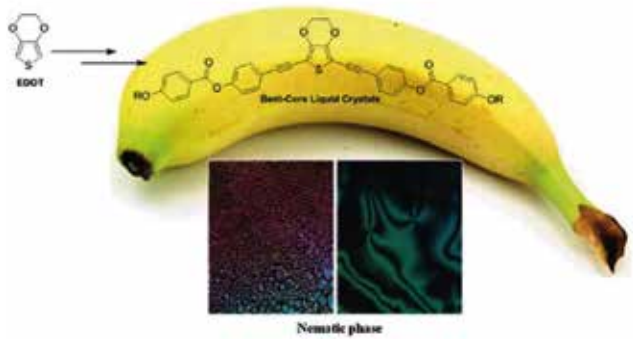
Since their discovery, considerable work has gone into understanding their structure-property relationships, which hold the key for the myriad applications involving LCs. Researchers within the SCM group at RRI have done pioneering work in LCs and that tradition still continues today with research in 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 2016-17 was on developing new building blocks for novel LCs, viscoelastic phase separations in LC mixtures, noble metal nanoparticle-LC hybrids, photovoltaic applications of LCs and phenomenological theory of instabilities.

Design, Synthesis and Structure-property relationships of Bent core Liquid crystals

Ethylenedioxythiophene as a novel central unit for bent-core liquid crystals

During 2016-17 SCM members have discovered that ethylenedioxythiophene (EDOT) can be used as a central unit for the synthesis of bent-core liquid crystals (BC LCs). The EDOT-based BC LCs was prepared via Sonogashira coupling reaction. Polarizing optical microscopy, differential scanning calorimetry and X-ray diffraction measurements were used to study the mesophase behaviour of all the compounds. It was found that EDOT-based three-ring compounds were non-liquid crystalline, while all the four derivatives of five-ring series, including a branched alkoxy chain derivative, displayed enantiotropic nematic phase over wide temperature range. The bend angle of these compounds was about 153°, which falls in-between typical rod-like and banana liquid crystals. The transition temperature of branched alkoxy chain compound was found to be lower than straight alkoxy chain compounds. [Ashwathanarayana Gowda and Sandeep Kumar]

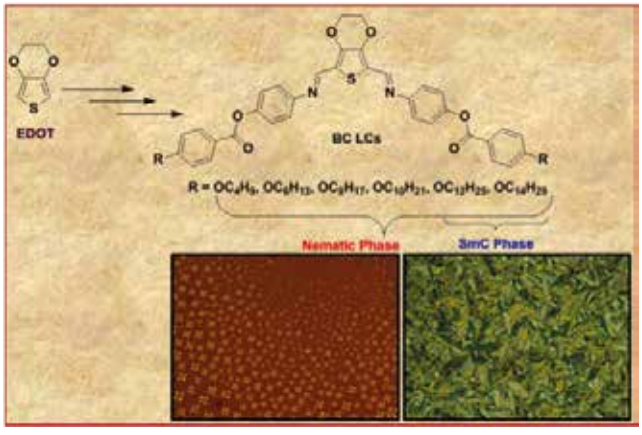


Nematic phase forming novel EDOT-based liquid crystals

Synthesis and mesomorphic properties of novel Schiff base liquid crystalline EDOT derivatives

In a related study, novel banana liquid crystals derived from ethylenedioxythiophene (EDOT) central unit described above were encompassed with a Schiff base. Structural characterization of these compounds was carried out from their spectral and elemental analysis. Physical properties of all the newly synthesized compounds were investigated by polarizing optical microscopy, differential scanning calorimetry, thermogravimetric analysis, X-ray diffraction and Raman spectroscopy. EDOT bearing three-ring Schiff base bent-core compounds were found to be non-mesomorphic, whereas all the Schiff bases containing five-rings exhibit

enantiotropic mesophase behaviour. The higher homologues displayed long range nematic phase along with a smectic C phase at lower temperature, while the lower homologues exhibited only N phase. This observation was corroborated by XRD data. Since the bend angle in these compounds lies in-between that of calamitic LCs and banana LCs, the molecules escape from the polar order packing observed in typical bent core LCs.
[Ashwathanarayana Gowda, Sandeep Kumar and Arun Roy]



Nematic and smectic phase forming novel EDOT-based liquid crystals

Evidence for cybotactic clusters in the nematic phase formed by bent-core molecules by x-ray diffraction studies

Polar nematic phases exhibiting ferroelectric-like switching behavior can be of interest for a wide range of display applications and development of new functional materials for optoelectronics. Although there have been several attempts, the realization of such a polar nematic phase is, however, highly debated. There have been some studies recently, which have attributed the ferroelectric-like switching in the nematic phase of an achiral unsymmetrical bent-core liquid crystal to the formation of smectic C like cybotactic clusters in the nematic phase. Recent electro-optic and dielectric studies on a homologous series of four-ring bent-core liquid crystals, with 4-n-alkoxy salicylideneimine unit at one end of the molecule linked to a central phenyl core substituted with a methyl group in transverse position and linked by an ester group at meta position to the azobenzene wings, had shown some evidence for electro-optic switching in the nematic phase.

To gain a better understanding of the electro-optic switching SCM staff at the Institute performed detailed X-ray diffraction studies on the compound with alkyl chain length n=16 belonging to this series and exhibiting the nematic and orthogonal smectic phases. When the sample was initially cooled from the isotropic phase, down to ~3^0 C above the isotropic–nematic phase transition, only a diffuse wide angle peak was observed in the X-ray diffraction pattern. Upon lowering the temperature in the isotropic phase, a distinct peak was observed in the small angle region at ~2^0 C above the temperature at which the nematic phase forms, which indicated the formation of clusters with smectic type of ordering. On further decrease of temperature within the nematic phase, the small angle peak becomes sharper confirming the presence of cybotactic clusters in the nematic phase. This peak becomes even more enhanced at the transition into the smectic phase, showing a clear change over from the cybotactic nematic to a layered orthogonal smectic phase. In order to substantiate this quantitatively an analysis of the small-angle-scattering data was carried out by fitting the peaks to Lorentzian curves. The correlation length was calculated according to the Scherrer equation and the cluster size/correlation length estimated in the transversal direction. The correlation length was found to increase gradually in the nematic phase, confirming the existence of the short range order which was found to be in agreement with the dielectric and electro-optic observations.
[Sharmistha Ghosh, Raj Kumar Khan, Srikanth Turlapati, Nandiraju V. S. Rao, Pramod Tadapatri and R Pratibha]

Smectic nano clusters in the nematic mesophases of dimeric compounds

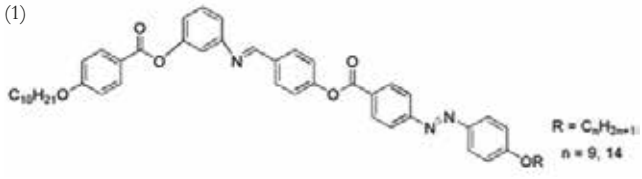
Recent research was on studying the effects of different lateral substituents at different locations and direction of ester linkage, on the mesogenic properties in several new homologous series of dimeric compounds. Specifically, two rod-like non-mesogenic laterally substituted azo moieties were connected to each other by an alkylene spacer through ester linkages. In all these dimers, the end alkoxy chain length was kept constant and the length of the spacer chain was varied. An odd-even effect of methylene groups in the spacer chain was observed. Additionally, a clear effect of lateral substituents at different positions and direction of ester linkages, on the mesomorphic properties was observed. These dimers exhibited nematic and smectic mesophases. X-ray diffraction studies revealed that the nematic phases are composed of smectic nano clusters (N_{cybC}) irrespective of whether a smectic phase exist below the nematic phase or not. Bent-core phases were not observed in these dimers and they were photo-switching both in solution and in their nematic mesophases. The photo-induced effect is more pronounced in the case of dimers with odd spacer when compared to those with even spacer. Gelation properties of these dimers were also investigated and a comparison of liquid crystalline and gelation properties of these dimers was made with similar but laterally unsubstituted dimers.
[M. Monika, Veena Prasad and Arun Roy]

Novel smectic phases exhibited by bent core hockey stick shaped molecules

Previously, novel smectic phases exhibited by bent core hockey stick shaped (BCHS) molecules were studied at the

Institute. Research during 2016-17 was on studying a new series of BCHS molecules in collaboration with chemists. These studies not only confirmed the existence of novel pseudopolar smectic reported earlier but also showed new phases and provided information on the stability of these phases on the chain length of the homologous series of compounds. Two BCHS compounds A9 and A14 of an azo substituted series showing unusual phase behavior were studied by various experimental techniques such as Polarizing Optical Microscopy (POM), X-Ray Diffraction (XRD), Differential Scanning Calorimetry (DSC), Switching-Polarization Current measurements and Optical Transmission properties, Dielectric-Optic measurements. Based on these experimental studies it was established that the compound A9 showed the following phase sequence on varying the temperature: Iso (125.3^{0}C) SmA (124.3^{0}C) SmCM*(118.6^{0}C) SmCS (99.6^{0}C) Cry. The XRD studies further confirmed the lamellar smectic order in the mesophases of the compound A9. The compound A14 with longer chain length exhibited two pseudopolar tilted smectic phases, which displayed remarkable electro optic response under the application of electric field as shown in the figure.
[Deepshika Malkar, B. K. Sadashiva and Arun Roy]

(1)



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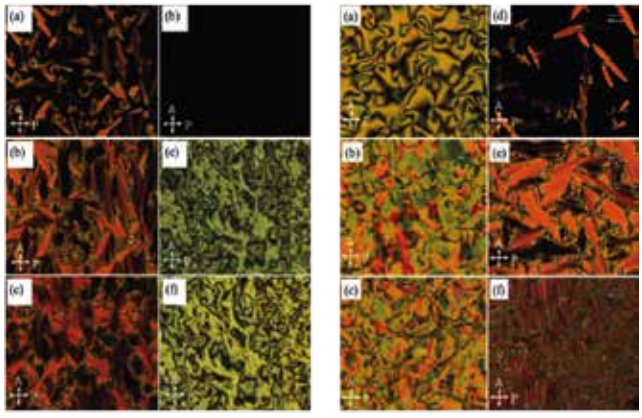


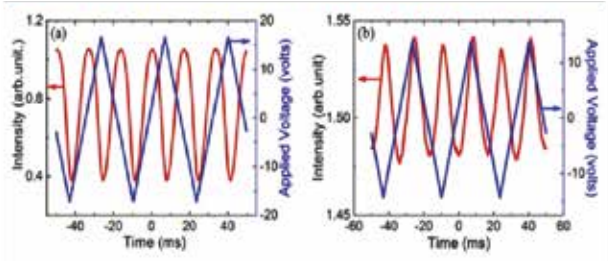


Figure 1: Molecular structure of BCHS molecules.

Figure 2: POM optical texture for compound A9 under cross polarization for planar aligned sample (a) SmA phase with coexistence of isotropic phase at 124.7 C (b) uniform focal conic fan texture in SmCM phase at 122 C and (C) broken focal conic fan texture SmC S phase at 114 C and for homeotropic aligned sample (d) dark homeotropic texture in SmA phase (e) schlieren texture dressed up with undulations in SmCM phase at 122 C and (f) clear schlieren texture in SmCS phase at 114 C.

Figure 3 POM optical textures under cross polariser of compound A14 for homeotropic alignment: (a) schlieren texture just below clear temperature (b) birefringent schlieren texture in SmC_AZ_A phase (c) birefringent schlieren texture with domains in SmC_IZ_I phase and for planar: (d) SmC_A Z_A phase just below clear temperature (e) fully grown focal conic fan texture in SmC_AZ_A phase at 118 C and (f) irregular band structure in SmC_I Z_I phase.

Figure 4: The Bottom plot shows the electro-optic response in different phases of compound A14 under the application of an electric field of frequency 30 Hz in (a) SmC_AZ_A phase at 124 C and (b) SmC_IZ_I phase at 102 C.

Discotic Liquid Crystals derived from Polycyclic Aromatic Cores: From Smallest Benzene to utmost Graphene

During the past decades there has been many breakthroughs in research on liquid crystals (LCs) as well as significant amplification in the application of LCs. As a result of this, LCs are currently attracting considerable attention of scientists from all over the world on the varied facets of LCs. Researchers in the SCM group at the Institute, along with collaborators, have over the year written a review article on recent developments in the field of discotic liquid crystals (DLCs), with specific focus on DLCs derived from four main aromatic cores: benzene, triphenylene, hexabenzocoronene and graphene. The review presented the outlook for these emerging two-dimensional organic semiconductor materials with relevant scientific applications.
[Ashwathanarayana Gowda, Manish Kumar and Sandeep Kumar]

Liquid Crystals - Phase separation dynamics and Pattern formation

Viscoelastic phase separation in dynamically asymmetric liquid crystalline mixtures

Phase separation is a physical phenomenon observed in a wide variety of materials and usually described by the model B for solids and model H for fluids. While in solids, concentration changes are considered to occur mainly by material diffusion, in fluids, both diffusion and flow are involved. Usually for a binary mixture, both these models assume the same dynamics for the two components. But this assumption of dynamic symmetry is not always valid in real complex fluids. The viscoelastic model was proposed by H. Tanaka to describe phase separation behaviour of mixtures composed of fast and slow components. The phase separation process in this case is attributed to an intrinsic dynamic asymmetry between the

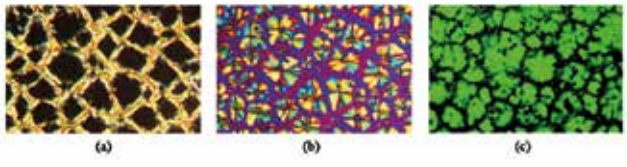
components and involves a coupling between the deformation rate associated with the phase separation and the rheological relaxation rate of the phase that is richer in the slower component. One of the reasons why such an asymmetry can arise is the large size difference between the constituents.

The phase separation process is associated with a variety of growth morphologies. In addition to the frequently observed droplet and bicontinuous structures, cellular and network structures have also been observed. In binary mixtures, apart from the classical mechanisms of phase separation like diffusion and minimization of interfacial energy, viscoelastic effects are also known to influence pattern formation. Evidence for this has been observed in the case of polymeric solutions where the larger polymer molecules move much more slowly than the solvent molecules. Some other systems in which dynamic asymmetry have been found to cause viscoelastic phase separation (VPS) are colloidal suspensions and surfactant solutions exhibiting a lyotropic lamellar phase. However, most of the well-known examples exhibiting the phenomenon of VPS are from disordered isotropic materials. The visualization of VPS can be more dramatic when the two components exhibit liquid crystalline phases. The anisotropic nature and rich variety of phase transitions characterized by myriad optical textures and defect structures in liquid crystals can make such a phase separation process more spectacular than in isotropic liquids.

Recent research at the Institute has shown evidence for such an effect in some binary mixtures composed of liquid crystals made of rod-like (R) and bent-core (BC) molecules. A special binary system consisting of the commercial compound 8OCB (4-*n*-octyloxy 4'-cyanobiphenyl)) made of R molecules, which exhibits the nematic and smectic A phases, and BC20 belonging to the homologous series 4-*n*-Octyloxyphenyl-3'-(2-fluoro-4-(3-fluoro4-*n*-alkoxy-benzo yloxy)biphenyl-4-carboxylates and made of BC molecules exhibiting the $B7_A$ phase has been used.

The difference in dynamics at phase separation of these two types of molecules was found to manifest in the form of cellular structures (CSs). The unique feature here was the formation of CSs arising from differences in the size and shape of the constituent R and BC molecules and was mainly driven by dissimilarities in flow and rotational viscosities of the molecules. This study demonstrated that phase segregation in such mixtures could be strongly affected by viscoelastic effects. Although some studies had hinted at unusual viscoelastic behavior leading to nanophase segregation in some mixtures of R and BC molecules, such a macroscopic phase segregation process manifested by the occurrence of two coexisting phases forming CSs had not been observed earlier. This was possible mainly because of the special molecular structure of the BC molecules used in the present system. First, the two arms of the bent aromatic core are not symmetric with respect to the central ring. Further the presence of fluorine atoms in one of the arms of the aromatic core has an effect on the conformations of the molecule, which in turn can influence the viscous behaviour. In addition, the extremely long alkyl chain attached to one arm of the rigid core can be expected to slow down the rheological relaxation rate of the BC molecules at the phase transition, resulting in dynamic asymmetry between the smaller rod-shaped 8OCB molecules and the larger BC20 molecules, leading to VPS. In essence, because of the longer rheological time of the slower BC component, viscoelastic relaxation generated internal stresses within the R and BC mixtures resulting in a coupling between stress and diffusion, which drives the VPS process.

The heterogeneous structure was characterized by optical and confocal microscopy along with X-ray diffraction studies and found to be comprised of several coexisting liquid crystalline phases. The striking resemblance to CSs of biological systems further enriched by topological defects is unique to this system. The morphology and stability of the CSs are dictated by the smectic ordering influenced by the relative concentration and mutual orientation of the R and BC molecules. This type of phase separation process has the potential to provide a possible technique for forming functional ordered assemblies of nanoparticles embedded in a liquid crystal matrix.
[Anjali S and Pratibha R]



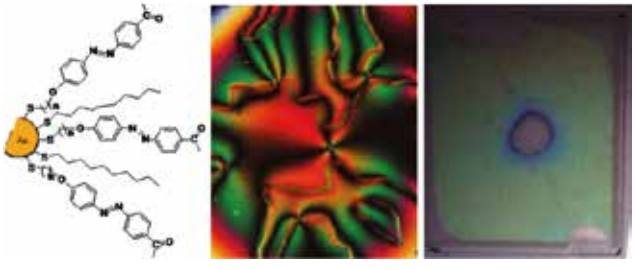
Cellular structures (CSs) occurring in a binary mixture of liquid crystals made of R and BC molecules. (a) Immediately after phase separation, crossed polarizers. (b) Same sample as in (a), but 15 min later after the formation of defects in the homeotropic region generated in order to preserve layer compatibility between smectic phases in the enclosed and outer connected regions, crossed polarizers and full wave plate with slow axis at 45 deg to the polarizer. (c) Confocal laser scanning microscope image of CSs in a sample doped with the fluorescent dye BTBP.

Liquid Crystal Nanoscience

Research efforts at RRI have 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, storage and photovoltaics.

Synthesis of new liquid crystals embedded gold nanoparticles for photo-switching properties

Recent research at the Institute has unearthed attractive photoisomerization behavior in a new series of liquid crystals decorated gold nanoparticles whose molecular architecture has azobenzenes moieties as the peripheral units connected to gold nanoparticles (Au NPs) via alkyl groups. These molecules exhibited attractive photoisomerization behavior in which trans-cis transition takes about 15 s whereas the cis-trans transition requires about 45 min for compounds with Au nanoparticles. Additionally, the extent of reversible isomerization did not decay after 10 cycles, which proved that the photo-responsive properties of Au nanoparticle compounds were stable and repeatable. Investigations of the morphology and mesomorphic properties of these hybrids showed that enantiotropic smectic A phase was displayed by the thiol terminated azobenzene ligand molecules, whereas gold nanoparticles passivated with these ligands exhibit nematic and smectic A phase with monotropic nature. This study showed that these materials may be suitably exploited in the field of molecular switches and optical storage devices.
[Md Lutfor Rahman, Tapan Kumar Biswas, Shaheen M. Sarkar, Mashitah Mohd Yusoff, A.R. Yuvaraj, Sandeep Kumar]



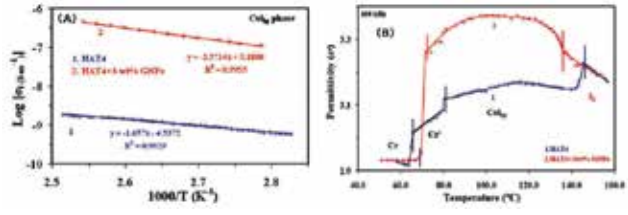
New molecules, Au NP azobenzene liquid crystals (texture at middle can be adopted for optical storage devices (ITO cell in the image on the right). Gray color spot in the middle of ITO cell is the UV irradiated area, which is a disordered isotropic phase, whereas the greenish area is protected from the light by a mask.

Self-Assembly of Silver and Gold Nanoparticles in a Metal-Free Phthalocyanine Liquid Crystalline Matrix: Structural, Thermal, Electrical and Nonlinear Optical Characterization

The properties of self-assembled supramolecular structures change remarkably upon the dispersion of a minute amount of metal nanoparticles in them. SCM researchers have investigated, for the first time, the effect of dispersing alkyl thiol functionalized group-XI metal nanoparticles (silver and gold) in a phthalocyanine-based discotic liquid crystal on their structural, electrical, thermal and nonlinear optical transmission properties, and supramolecular order. Uniform dispersion of about 0.5-3% metal nanoparticles in the columnar matrix resulted in an increase in the electrical conductivity of the system by two to four orders of magnitude, without disrupting the mesophase. Additionally, these nanocomposites displayed enhanced nonlinear optical absorption, when measured under excitation by nanosecond laser pulses at 532 nm. These studies showed that self-assembling supramolecular soft nanocomposites have potential applications in optoelectronic devices such as thin film transistors, photovoltaic solar cells, and optical limiters.
[Ashwath Narayana Gowda, Manish Kumar, Anitta Rose Thomas, Reji Philip and Sandeep Kumar]

Effect of high concentration of colloidal gold nanoparticles on the thermodynamic, optical and electrical properties of 2, 3, 6, 7, 10, 11-hexabutyloxytryphenylene discotic liquid crystalline material

Recent research at the Institute has shown a decrease in the band gap upon dispersion of Au nanoparticles in a plastic columnar discotic liquid crystal (DLC), namely 2,3,6,7,10,11-hexabutyloxytryphenylene (HAT4). Due to the addition of GNPs in the triphenylene-based DLC (HAT4), temperature for transition from columnar hexagonal to isotropic liquid phase appreciably decreased; however, the transition temperature from crystal to columnar hexagonal phase did not change drastically. Interestingly, the ionic conductivity of nanocomposites showed an increment by two orders of magnitude due to doping of GNPs.
[Mishra M., Kumar, S., Dhar, R]



(A) Variation of the ionic conductivity with inverse of temperature (Arrhenius plot): (1) HAT4; (2) for HAT4 + 3.0 wt% GNPs; (B) Variation of the permittivity (ε') with temperature (°C): (1) HAT4; (2) HAT4 + 3.0 wt% GNPs

Thermodynamic study of a plastic columnar discotic material 2, 3, 6, 7, 10, 11 hexabutyloxytriphenylene dispersed with gold nanoparticles under elevated pressure

Research during 2016-17 was towards determining how elevated pressure could be used to modify the physical properties of plastic columnar DLC (HAT4) and their nanocomposites via changes in inter- and intra-molecular distances in discotics. It was found that the columnar hexagonal plastic to isotropic liquid (Colhp–IL) phase transition temperatures and enthalpy decreased with increasing pressure. However, crystal to plastic columnar hexagonal (Cr–Colhp) transition temperature remained almost unchanged for pure DLC and their nanocomposites. Such a study of the effect of pressure on the phase behaviour

of DLC was undertaken to elucidate the nature of the mesophase behaviour.
[Pratibha Tripathi, Mukesh Mishra, Sandeep Kumar and Ravindra Dhar]

Photo-induced characteristics of azobenzene based gold nanoparticles

With the aim of studying the photoisomerization effect, SCM staff synthesized azobenzene based gold nanomaterials through Au-S bonding between thiol substituted azobenzene derivatives with gold nanomaterial core. Absorption studies showed that photosaturation occurred at ~24 s with back relaxation taking ~315 min. The lengthening of photo switching time duration was attributed to steric hindrance developed by the multiple attachments of azobenzene molecules to the central gold nanoparticle core. A better understanding of the hybrid structure was obtained from nuclear magnetic resonance, IR, transmission electron microscopy and UV-Vis spectroscopic techniques. This study on the light induced characteristics of azobenzene based gold nanoparticles could have potential applications in photo switching applications.
[Yuvaraj Rajkumar Aralapura, Md Lutfor Rahman, Mashitah Mohd Yusoff and Sandeep Kumar]

Supramolecular Nanocomposites: Dispersion of Zero-, One- and Two-dimensional Nanoparticles in Discotic Liquid Crystals

One area of active research has been on hybridization of discotic LCs with various zero-, one- and two-dimensional metallic and semiconducting nanoparticles to alter and improve their thermal, supramolecular and electronic properties. During 2016-17 SCM researchers have published a review article, which provides an overview of the work carried out at the Institute on the dispersion of various metallic, semiconducting and carbon nanoparticles in discotic liquid crystals. The review gave an introduction to self-organizing supramolecular liquid crystalline materials, with an emphasis on discotic liquid crystals, followed by a description of various discotic liquid crystal-nanoparticle hybrid systems and the enhancement in their physical properties such as conductivity, photoconductivity, absorbance, etc.
[Sandeep Kumar]

Functional Liquid Crystalline gels

Liquid crystal gels generally consist of a dispersed network of fibrous aggregates of an organic gelator in a liquid crystal solvent. Interesting self-assembled structures can be obtained depending on the gelator and the structure of the liquid crystalline phase. These liquid crystal gels can have interesting applications like improved response to electric fields and mechanical stability. Hybrid systems of these liquid crystal gels incorporating nano particles can aid in improved performance in soft matter photonics. SCM staff have recently initiated studies on some of these gels. Preliminary investigations showed evidence for the formation of novel types of regular orientation patterns and induced phases. These are being studied in detail using a variety of experimental techniques like scanning electron microscopy and dielectric spectroscopy.
[Neha Bhagwani, Prutha Ra and Pratibha R]

Self-assembled CNT-polymer hybrids in single-walled carbon nanotubes dispersed aqueous triblock copolymer solutions

RRI researchers undertook scanning electron microscopy (SEM), differential scanning calorimetry (DSC), small angle X-ray scattering (SAXS), electrical conductivity and 1H NMR studies, as a function of temperature, on single-walled carbon nanotubes (SWCNTs) dispersed aqueous triblock copolymer (P123) solutions. The single-walled carbon nanotubes in this system aggregate to form bundles and the bundles aggregate to form net-like structures. Depending on the temperature and phases of the polymer, this system exhibits three different self-assembled CNT-polymer hybrids. CNT-unimer hybrid was observed at low temperatures, CNT-micelle hybrid at intermediate temperatures wherein the polymer micelles are adsorbed in the pores of the CNT nets, and another type of CNT-micelle hybrid at high temperatures wherein the polymer micelles are adsorbed on the surface of the CNT bundles. The DSC thermogram showed two peaks related to these structural changes in the CNT-polymer hybrids. The temperature dependence of the 1H NMR chemical shifts of the molecular groups of the polymer and the AC electrical conductivity of the composite also showed discontinuous changes at the temperatures at which the CNT-polymer hybrid's structural changes are seen. Interestingly, for a higher CNT concentration (0.5wt.%) in the system, the aggregated polymer micelles adsorbed on the CNTs exhibit cone-like and cube-like morphologies at the intermediate and at high temperatures respectively (see accompanying figure).
[Vijayaraghavan D]

Self-assembled CNT-polymer hybrids consisting of cone-like and cube-like morphologies in 0.5 wt.% CNT dispersed aqueous triblock copolymer (P123) solution.

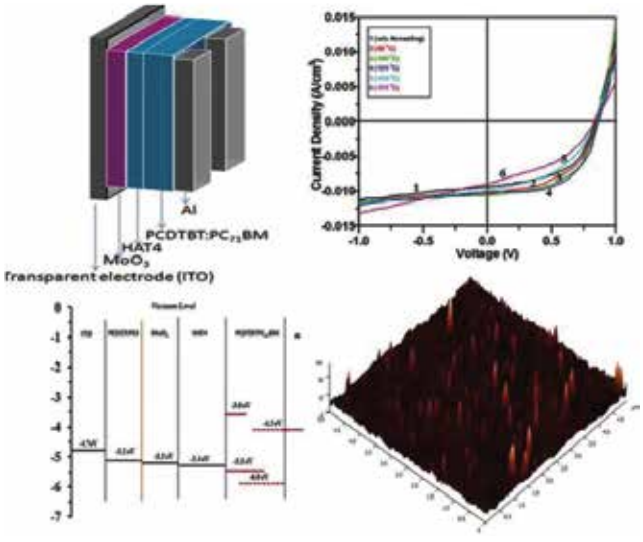
Magnetic birefringence studies on a carbon nanotubes-lyotropic liquid crystal composite: Effect of applied magnetic field on the hexagonal –isotropic phase transition temperature

Magnetic birefringence studies were carried out at RRI as a function of temperature on 0.14 wt.% single walled carbon nanotubes (SWCNTs) dispersed lyotropic liquid crystal (LLC) consisting of 50 wt.% Triton X-100 (TX-100) in water. At zero magnetic field, the optical birefringence of the composite showed a peak at the hexagonal to isotropic (HI) phase transition temperature of the composite. For low applied fields, the peak shifts towards the lower temperatures and for higher applied fields (>0.5 Tesla), the peak shift exhibits a reversal and shifts towards the higher temperatures (towards the zero field position). Since the birefringence peak occurs at the HI phase transition temperature of the composite at the zero magnetic fields, it was conjectured that the observed birefringence peak shifts on the temperature scale is related to the changes in the HI phase transition temperature of the composite due to the applied magnetic fields. The result indicates that the hexagonal ordering of the LLC micelles in the composite is destabilized at low fields and stabilized at high fields. It was inferred that both the decrease in the viscosity of the composite and the ordering of the CNTs in the composite with increasing applied fields might be responsible for this behavior.
[Vijayaraghavan D]

Liquid Crystals – Photovoltaic applications

Another important area of research given the over dependence on fossil fuels and their contribution to global climate change is alternate energy sources. The main player, in the Indian context, given that the countryside is bathed in abundant sunshine, could be solar energy. SCM researchers at the Institute, in collaboration with peers, are working on developing liquid crystals for photovoltaic applications. During 2016-17, two designs of bulk heterojunction solar cells were studied: (1) fabricated by inserting a discotic triphenylene derivative into poly (3-hexylthiophene): [6, 6]-phenyl-C61-butyric acid methyl ester with a buffer layer of molybdenum oxide inserted between anode and active layer; this gave a power conversion efficiency of 2.0% under one-Sun condition. (2) Bulk heterojunction photovoltaic cells based on composites of copolymer poly[N-90-heptadecanyl-2,7-carbazole-alt-5,5-(40,70-di-2-thienyl-20,10,30-benzothiadiazole)] and the fullerene derivative [6,6]-phenyl C71-butyric acid methyl ester with an inserted layer of discotic liquid crystalline material (2, 3, 6, 7, 10, 11-hexabutyloxytriphenylene) between the interface of active layer and hole transporting layer. Power conversion efficiency of 5.14% was achieved for these photovoltaic solar cells containing self-organized discotic liquid crystal layer of 30 nm thickness, under one-Sun condition, which is substantial improvement as compared to earlier works. The mobility of holes in the discotic liquid crystal inserted devices was found to be of the order of 10^{-6} cm^2 V^{-1} s^{-1} due to which high values of current density was achieved.

The effect of varying the thickness of the liquid crystal layer and annealing on these solar cells was also studied. Post annealing the bulk heterojunction devices with discotic liquid crystal layer of thickness 20 nm in them yielded an open circuit voltage of 0.41 V, short circuit current density of 17.0 mA cm^{-2}, a Fill factor of 0.35 and power conversion efficiency of 2.5%.
[Manisha Bajpai, Neelam Yadav, Sandeep Kumar, Ritu Srivastava and Ravindra Dhar]



Design and characteristics of bulk heterojunction photovoltaic cells based on composites of copolymer PCDTBT and PCBM with an inserted layer of discotic liquid crystal

Liquid crystals in photovoltaics: a new generation of organic photovoltaics

In another review article published in 2016-17, SCM research staff have presented an overview of the developments in the field of organic photovoltaics (PVs) with liquid crystals (LCs). The review provides an introduction to the PV and LC fields followed by application of various LCs in organic PVs along with details of LCs used in bilayer solar cells, bulk heterojunction solar cells and dye-sensitized solar cells. All the liquid crystalline materials used in PVs along with the efficiency of solar cells were tabulated. An outlook into the future of this newly emerging, fascinating and exciting field of self-organizing supramolecular LC PV research was discussed in the review.
[Manish Kumar and Sandeep Kumar]

Liquid Crystals – Phenomenological theory

Elasticity of smectic liquid crystals with in-plane orientational order and dispiration asymmetry

The Nelson-Peliti formulation of the elasticity theory of isolated fluid membranes with orientational order emphasizes the interplay between geometry, topology, and thermal fluctuations. Fluid layers of lamellar liquid crystals such as smectic-C, hexatic smectics, and smectic-C* are endowed with in-plane orientational order. Theorists in the SCM group have extended the Nelson-Peliti formulation so as to bring these smectics within its ambit. Using the elasticity theory of smectics-C* it was shown that positive and negative dispirations (topological defects in Smectic-C* liquid crystals) with strengths of equal magnitude have disparate energies — a result that is amenable to experimental tests.
[Jaya Kumar A, Buddhapriya Chakrabarti and Yashodan Hatwalne]

Topological instability in lyotropic smectic-A liquid crystals

Research on topological instabilities in lyotropic smectic-A liquid crystals under compression is motivated by the observed structure of the rough endoplasmic reticulum in biological cells. During 2016-17, SCM research staff and collaborators have obtained the "phase diagram" of the different possible structures in parameter space. Currently efforts are towards refining the phase diagram using numerical methods.
[Jaya Kumar A, Yashodhan Hatwalne and Rahul Pandit]

Phenomenological theory of Membranes and Polymer crystallization

Morphology of polymer crystallites

Polymer crystallites exhibit diverse morphologies. Melt-grown crystallites of achiral polymers such as polyethylene have spherulitic structures made up of helicoidal lamellae that break chiral symmetry. This has been a long-standing problem in polymer physics (see, for example, B. Lotz and S. Cheng, Polymer **46**, 577 (2005) and references therein). Y. Hatwalne and M. Muthukumar (Phys. Rev. Lett. **105**, 107801 (2010)) provided a phenomenological theory. Apart from this morphology, polymer crystallites grow in the form of planar sectored structures, tents, chairs, and scrolls. The stability of these structures has been a long-standing problem (over sixty years) in the field of polymer physics, and no unified theoretical framework explaining the stability of observed morphologies exists.

The long-term aim of theorists in the SCM group is to construct a unified phenomenological theory that accounts for the stability of all the observed morphologies. It was realized that the interplay between elasticity, geometry, and topology played a crucial role in stabilizing the observed morphologies. Work on the planar, sectored morphology was completed, and has been published. Current efforts are now towards studying the tent morphology of polymer crystallites.
[Jaya Kumar A., Yashodhan Hatwalne and M. Muthukumar]

Equilibrium of fluid membranes endowed with orientational order.

Minimization of the low-temperature elastic free energy functional of orientationally ordered membranes involves independent variation of the membrane shape, while keeping the orientational order (its texture) fixed. SCM research staff has proposed an operational and coordinate-independent method for implementing such a variation. Using the Nelson-Peliti formulation of elasticity that emphasizes the interplay between geometry, topology, and thermal fluctuations of orientationally ordered membranes, the research has enabled minimization of the elastic free energy to obtain equations governing their equilibrium shape, together with associated free boundary conditions. These results are essential for understanding and predicting equilibrium shapes as well as textures of membranes and vesicles, particularly under conditions in which shape deformations are large.
[Jaya Kumar A, Yashodhan Hatwalne and Buddhapriya Chakrabarti]

Biophysics

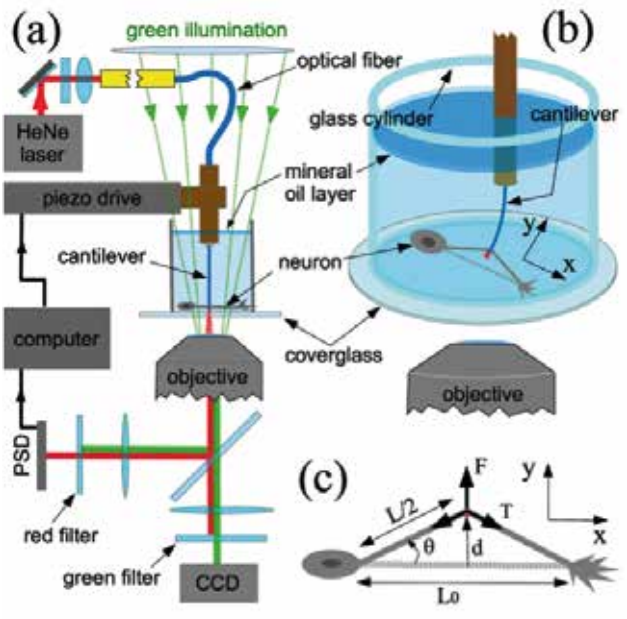
Biophysics of Axons

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). The diameter of the axon is only about a micron and in normal cells is almost constant for the entire length. This robustness may be because the diameter is set by a balancing act between two opposing physical factors; for example, the axonal membrane tension that tries to reduce the diameter is balanced by the entropic internal pressure due to the polymer gel that fills the interior (cytoskeleton). Moreover, maintenance of axonal plasticity requires that the neuronal cell should be able to retract and reform connections. Research of the biophysics group at RRI is trying to understand the reasons and the mechanisms behind axonal plasticity. They suspect that molecular motors and polymer dynamics are at work as they can generate stresses and flows to actively remodel the cytoskeletal structure. Research is focused towards answering the following questions: How do axons maintain a constant diameter over such long lengths? What determines the generation and redistribution of components during axonal growth? What drives the retraction of axons during axonal rewiring?

Additionally, investigations are also towards active axonal membrane dynamics and mechanics using a home-built optical tweezer setup. The approach includes the development of simple assays, image analysis techniques and fluorescence microscopy methods, use of genetic and biochemical tools, etc. As no readymade tools are available for some of these quantitative biophysics experiments, a significant part of the work is on the development of new tools. Some recent examples of such capability building are: a new type of force apparatus that can measure with pico-Newton and nano-meter precisions, and a compact device to apply rotational fluid shear stress to cells in order to quantify cell adhesion properties. A detailed description of the research undertaken by the Institute biophysics group during 2016-17 is given below.

Mechanical properties

Recent rheological measurements on axons using in-house built force apparatus in constant-strain mode showed that detachment dynamics of protein crosslinks is central to the



The setup consists of a cylindrical glass cantilever with length ~ 1 cm and diameter ~ 10 micron fabricated by etching one end of a single-mode optical fiber. The base of the cantilever is attached to a piezoelectric actuator and the tip is held in contact with the mid point of an axon as in schematic (a). The tip of the cantilever is tracked by imaging the red HeNe laser light exiting it on to a Position Sensitive Detector (PSD) and the cell is imaged using green illumination and a CCD camera. The axon, which is attached to the cover glass only at the two extremities, is stretched by displacing the base of the cantilever and the tension in the axon is measured by measuring the bending of the cantilever, as shown in images (b) and (c). A feedback loop algorithm is used to dynamically control the piezo in order to implement constant tension (T) or constant strain protocols.

dissipative behaviour (viscoelasticity) in axons. Using biochemical means, it was shown that cortical actin in an axon has a significant mechanical role, which is surprising since actin is not a major cytoskeletal component of the axon as compared with microtubules. Confocal microscopy imaging performed at the Institute, along with super-resolution imaging of axons by collaborators, revealed the presence of a spectrin skeleton in the neuronal cells. While there is no conclusive evidence for periodic ring like structure in cells > 24 hr in culture, older cells showed periodicity in some segments. Further improvements to the techniques could result in confirmation of these findings. Additionally tools were developed (Morpholino) to knock down spectrin in neurons and to test the mechanical response of these modified cells. Currently, efforts are towards making a GFP construct for spectrin using molecular biology techniques to enable fluorescence microscopy of live cells.

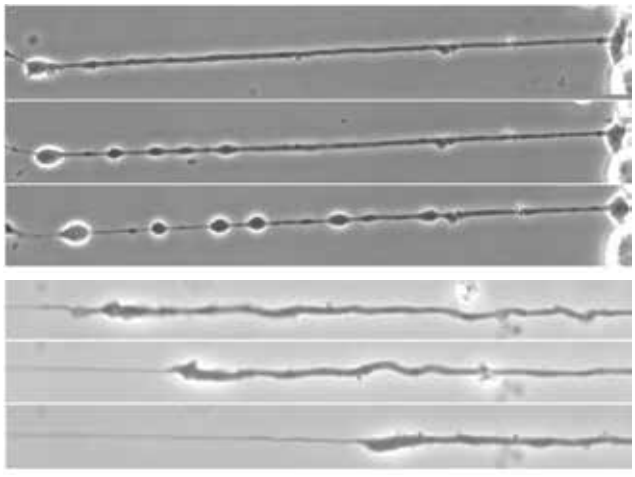
[Pramod Pullarkat, Sushil Dubey, Aurnab Ghose, Serene Rose David and Andrew Callan Jones]

Shape instabilities

During 2016-17 experiments were performed by SCM staff at the Institute with the aim of understanding the shape stability of axons. Specific biochemical agents were used to depolymerise actin-filaments or microtubules (biopolymers present inside the axon) for studying the resulting shape evolution. Two distinct responses were observed: (i) after microtubule depolymerisation the axon developed peristaltic radius modulations, (ii) when actin filaments were disrupted the axon exhibited a dynamic retraction front, which separated a thin region largely devoid of cytoskeletal components from a thick region into which these components were displaced. Interestingly, it was shown that both these shape dynamics could also be induced by local ablation of the axon using a nano-second laser pulse.

Additionally, using genetic means to express fluorescent synaptic vesicles it was shown that transport in axons is not affected by beading suggesting that "traffic jam" may not be the cause for beading as previously studies have suggested. Further evidence to support the above result was obtained by imaging intact microtubule tracks in beaded axon and, more importantly, by imaging vesicle transport in beaded axons using Synaptophysin-GFP as a genetically incorporated fluorescent probe. Laser ablation experiments have shown that these shape changes can be induced by breakages in the cytoskeleton. Performing such experiments in presence of a microtubule stabilizing agent showed that microtubule depolymerization may ensue due to the fresh (unprotected) end created by ablation and this could be the major cause for the shape evolution.

[Pramod Pullarkat, Anagha Datar, Roli Srivastava and Alka Bhat]

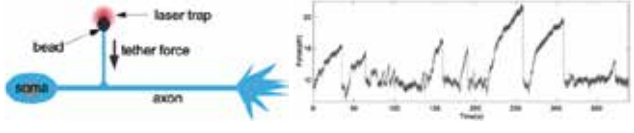


The two sets of image sequences above show the progression of axonal degeneration in response to a biochemical perturbation that resulted in the loss of microtubule filaments inside the axon. This and other experiments show th at these shape transformations, which result in axonal atrophy, are probably driven by membrane tension as a function of its stretching and bending elastic moduli. Microtubules stabilize the normal cylindrical shape of the axon due to its contribution to the bulk elasticity. Thus, conditions that affect microtubule stability results in instabilities in the system, which leads to atrophy of the axon. This work was done in collaboration with Prof. Jacques Prost (Institut Curie).

Membrane tether mechanics

Filopodia are tube like extensions generated by motile cells utilizing polymerization forces generated by actin bundles. The mechanism for filopodial dynamics-growth, contractility and retraction-is not well understood.

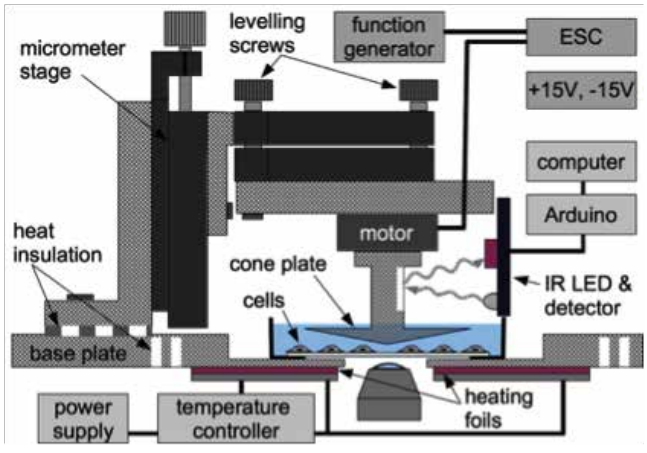
A series of experiments performed at the Institute during the past year has showed that membrane tethers pulled out of axons of neuronal cells can be used as model systems to study filopodial dynamics. This model system exhibits all major filopodia-like dynamics and is conducive to quantitative measurements of forces. These experiments have conclusively ruled out the role of myosin-II motors in force generation and have suggested a possible novel mechanism where twisting of actin filaments by actin binding proteins may be responsible for the contractile response. This is currently being tested.
[Pramod Pullarkat, Susav Pradhan and Satyajit Mayor]



Studies on force generation by polymerizing actin filaments inside a membrane nano-tube pulled out of axons using Laser Tweezers. These nano-tubes are a convenient system to study force generation by tubular processes called filopodia, which play an important role in axonal path finding.

Cell adhesion studies using an in-house shear device

SCM research staff has developed in-house a shear device for studying the effect of shear stress on cells along with fluorescence microscopy. The device itself is new—it is made using a computer hard-disk motor, which provides superb wobble-free performance and is very compact and hence mountable on any standard microscope including confocal systems. This device can differentiate changes in adhesion and can also be used along with micropatterning to create well-defined cell geometries. It was 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. The obtained experimental data along with a theoretical model developed by our collaborators, which considers stochastic bond detachment, is being prepared for communication.
[Pramod Pullarkat, Renu Vishavkarma, Namrata Gundiah and Gautam Menon]



Schematic of the home-developed compact, microscope mountable fluid shear stress device, which can be used to study cell adhesion properties. Such research is performed by measuring how cells grown on a surface detach under fluid shear stress. We have developed a theoretical model using which cell adhesion parameters can be extracted from experimental data. The theoretical modelling is done in collaboration with Gautam Menon (Institute for Mathematical Sciences, Chennai).

Nanoscale Biophysics of Biological Systems

Research in nanoscale biophysics of biological systems at RRI is primarily guided by the intriguing synergy of structures in biological systems and their functional dynamics. Staff at the Institute routinely use, as well as develop, novel nano-technological tools to decipher biophysical principles governing role of forces in cellular as well as molecular assemblies. Efforts are ongoing towards understanding the cellular mechanisms in sensing of forces as well as response of cells/molecules in model systems of self-assembly of proteins, DNA-protein complexes as well as whole cell stiffness. Research focus during 2016-17 was on developing various physical and molecular techniques to understand these problems.

Molecular Stitching at RRI

DNA handles are used as linkers or spacers in single molecule experiments to attach biomolecules on the surface. The immobilisation of the biomolecules on the surface using DNA handles can be used in single molecule manipulation in the lab via optical and magnetic tweezers, microfluidics as well as micro and nanopore experiments in order to study the mechanics of single molecule. Current research at the Institute accomplishes binding to the surface by interaction of the attached ligands (eg: Biotin, Digoxigenin) on the ends of the biomolecule with receptor molecules on the surface of the beads. (e.g., streptavidin and antidigoxigenin).
[Serene R., Divya M.V. and G.V. Soni]

The biological complexes assembled or prepared through these molecular biology techniques will be applied for biophysical force measurements. The force measurements may be carried out using techniques like nanopore, micropore, microfluidics, optical tweezers and AFM.

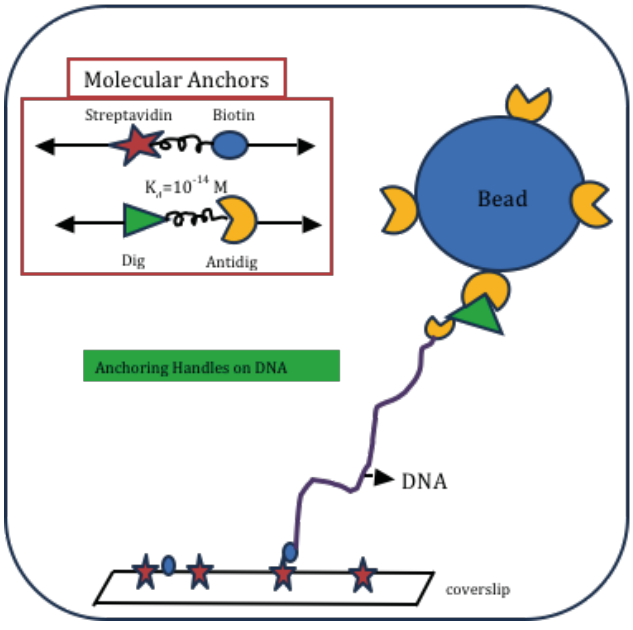
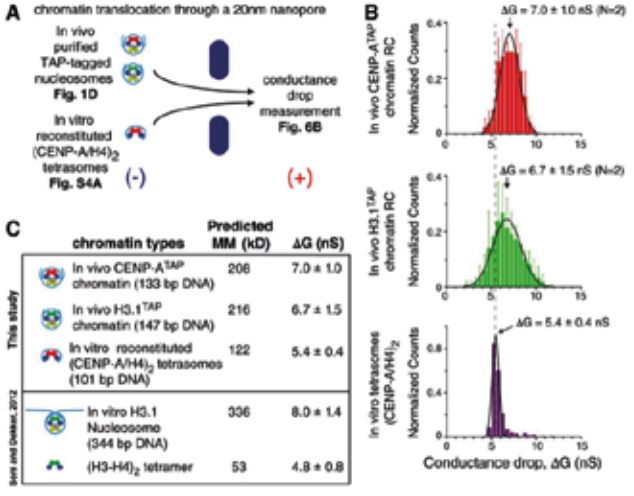


Figure shows schemes of anchoring molecules used to create molecular handles on DNA. SCM research staff are currently exploring streptavidin-biotin and Dig-AntiDig to create these molecular anchors for force spectroscopy measurements.

Measuring molecular volumes using a nanopore platform

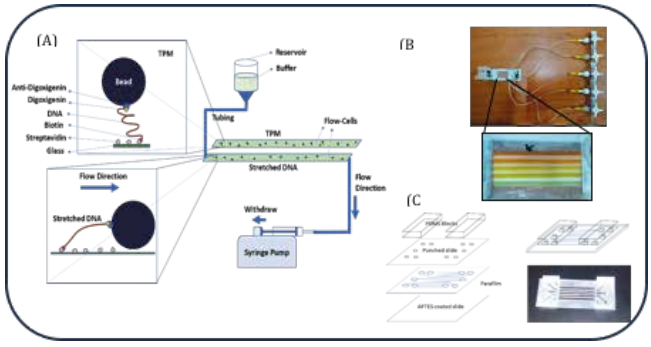
SCM research staff in collaboration with international peers have measured the molecular volume of CENPA nucleosomes. This work has paved the way to resolve longstanding questions in the field of nucleosome architecture during chromosome segregation in the process of cell division. This work was done in collaboration with Dekker Lab and Cleveland Lab.
[Yael Nechemia-Arbely, Daniele Fachinetti, Karen H. Miga, Nikolina Sekulic, Gautam V. Soni, Dong Hyun Kim, Adeline K. Wong, Ah Young Lee, Kristen Nguyen, Cees Dekker, Bing Ren, Ben E. Black and Don W. Cleveland]



Solid-state nanopore analysis of CENP-A chromatin reveals it to have the physical characteristics of nucleosomes. (A) Experimental design of chromatin translocation through a solid-state 20-nm-wide nanopore. (B) Conductance drop (ΔG) measurements during the translocation of (top, red) in vivo affinity-purified CENP-ATAP–containing chromatin particles (total events = 3,096), in vivo affinity-purified H3.1TAP-containing chromatin particles (middle, green; total events = 4,141), and (bottom, purple) in vitro–reconstituted (CENP-A/H4)2 tetrasomes (total events = 383). n = 2 from two independent datasets. Error bars represent SD. A fitted Gaussian distribution is overlaid in black. Fits were performed using the Levenberg–Marquardt algorithm to reduce the $\chi 2$ value. The reduced R2 values for the three fits were 0.94, 0.954, and 0.961. ΔG values represent the mean of the fitted Gaussian distribution, and the error bars are the width of the Gaussian fits. The vertical dashed line is the peak ΔG value for the tetrasome, as measured by the Gaussian fits. (C) Summary of the chromatin types measured in this study and previously (Soni and Dekker, 2012) using solid-state nanopore, along with their predicted molecular masses (with 4.5 kD added to each tagged histone to account for the S-peptide tag remaining after TEV cleavage). In vitro H3.1 nucleosomes were reconstituted on a 344-bp 601 nucleosome positioning sequence.

Microfluidics based Single Molecule DNA Stretching and Tethered Particle Motion

Force-extension measurements of biomolecules have broad application in biophysics and soft condensed matter research. They may be used to understand the mechanical properties of DNA as well as the changes in the properties of DNA on interaction with various proteins and ions. Single DNA molecules were tethered to the glass surface at one end and to microbeads at the other end, and the DNA extension was measured after hydrodynamic force was applied on the micro bead at different flow rates.
[Mahesh B.L. and G.V. Soni]



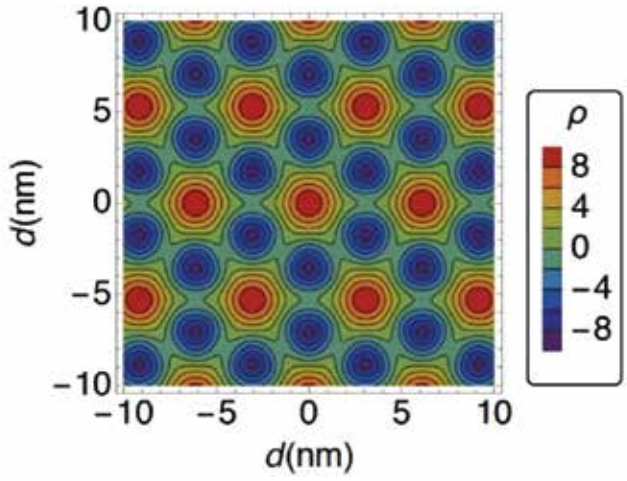
Fabrication of Microfluidics chip to measure effect of fluid-flow force on single DNA molecules. This microfluidic chip is mounted on a customized microscope to record the real time thermal fluctuation of a molecule to study its statistical physics properties. (A) shows the experimental schematic. (B) shows the setup. The inset shows 5 parallel microchannels fabricated next to each other for higher experimental throughput. Here the channels are filled with contrasting coloured fluids for display purposes. (C) shows the fabrication process.

Physics of Lipid Membranes and Polyelectrolytes

Two-dimensional crystals of linear macroions

Oppositely charged macroions self-assemble in aqueous solutions to form complexes. In the case of linear macroions, these complexes can have long-range translational order if at least one of them is sufficiently rigid. Such macroion crystals are somewhat analogous to ionic crystals, with the important difference that the stoichiometric constraint is lifted due to the presence of counterions. As a result, these systems can exhibit rich polymorphism. For example, it was found that structural changes of these crystals could be driven by varying the diameter of one of the species, as well as by changing the counterion. Current research efforts at RRI are towards calculating the energetics of these systems to understand these observations.

[Meera Thomas, Amitkumar Majhi and Raghunathan VA]



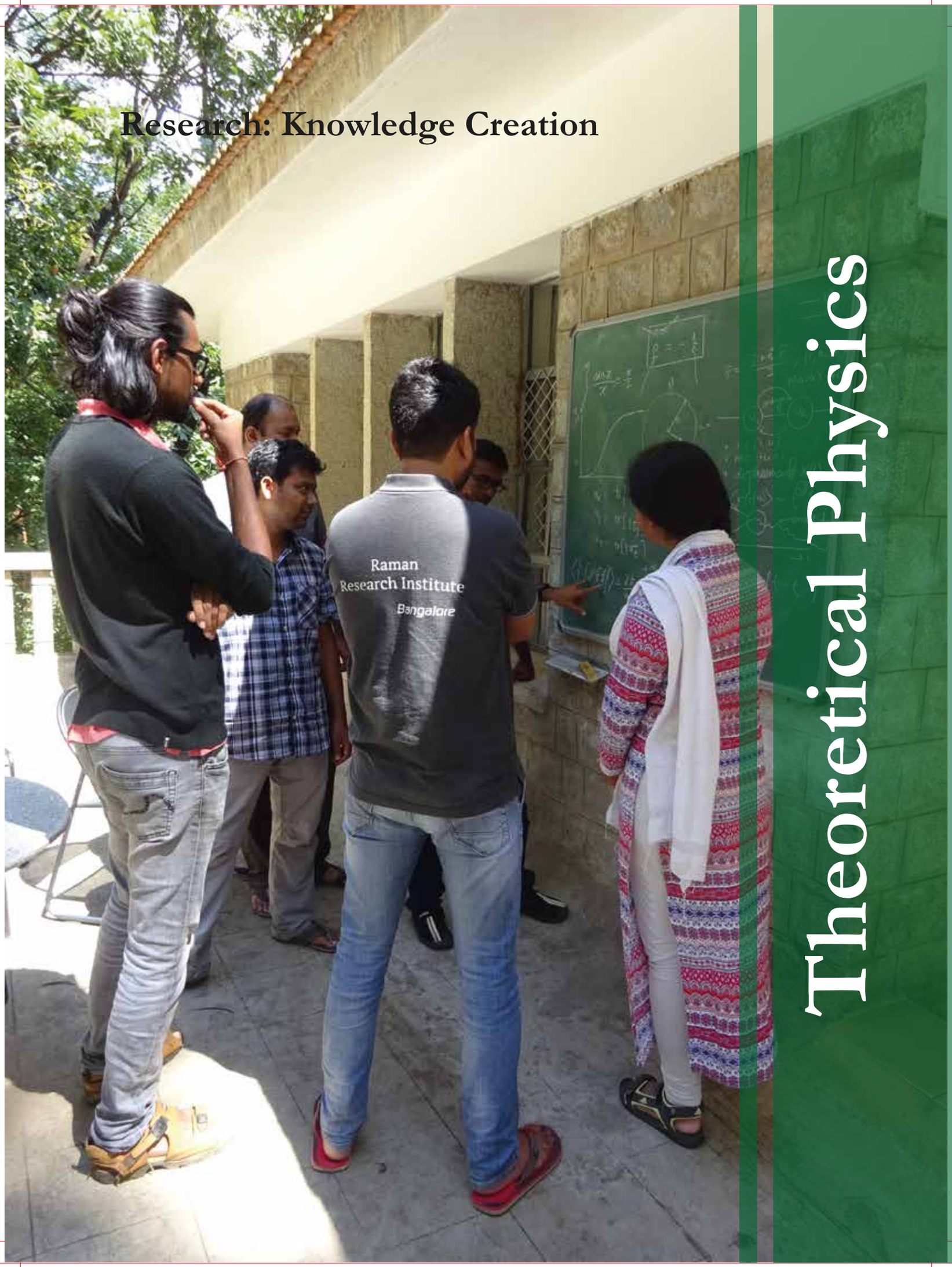
Electron density map of a hexagonal phase formed by a surfactant-DNA complex

Interaction of mononucleotides with lipid membranes

According to the RNA world hypothesis of the origin of life on earth, RNA-like self-replicating polymers can be synthesized non-enzymatically from mononucleotides in a lipid environment. Motivated by this, SCM research staff have been studying the interaction of uridine monophosphate (UMP) with phosphatidylcholine (PC) lipid membranes. UMP is found to adsorb on the PC membranes leading to an unbinding transition of the membrane stack. In addition, UMP enhances the ordering of the lipid molecules in the membrane. Efforts are underway to determine a detailed phase diagram of the mixed system in order to gain some understanding of the UMP-lipid interactions responsible for this behavior.

[Sreeja Sasidharan; Sudha Rajmani and Raghunathan VA]

Research: Knowledge Creation



Theoretical Physics

Overview:

Theoretical physics is an endeavor that attempts to make sense of the inner workings of nature, using the language of mathematics. The goal is to model and predict the behavior 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: Foundations of quantum mechanics, General Relativity, Quantum gravity and Statistical physics. 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 modeling stochastic search process. Additionally RRI theorists have fruitful ongoing collaborations in the above research areas with both national and international peers.

Focus 2016-17:

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.

Driven Inelastic Maxwell Gas in one dimension

It is well known that for a system of interacting particles in thermal equilibrium, the velocities of different particles are completely uncorrelated and the product of independent single-particle Maxwell distributions gives the joint distribution of the velocities. On the other hand, when a system is driven out of equilibrium, for example through application of a temperature gradient, nonzero correlations can build up between the velocities of particles. An important class of nonequilibrium systems is driven dissipative systems. An example of a dissipative system is granular gas, which in the absence of an external supply of energy loses energy continuously due to inelastic collisions. In the presence of external driving, for example in vibrated granular systems, one can obtain nontrivial steady states. A signature of nonequilibrium in this system is that the single-particle velocity distribution is no longer Maxwellian. It is thus interesting to ask about the nature of correlations among the velocities in this system.

Theorists at the Institute investigated this question in a simple lattice model of an inelastic gas in one dimension and calculated the exact form of the spatial correlation function of velocity for this model in its driven steady state.
[Sanjib Sabhapandit, V. V. Prasad, Abhishek Dhar and Onuttom Narayan]

Exact distributions of cover times for N independent random walkers in one dimension

Stochastic search processes are ubiquitous in nature. These include animals foraging for food, various biochemical reactions, such as proteins searching for specific DNA sequences to bind or sperm cells searching for an oocyte to fertilize. Several of these stochastic search processes often are modeled by a single searcher performing a simple random walk (RW). In many situations, the search takes place in a confined domain as the targets typically are scattered over the entire domain. Finding all these targets therefore requires an exhaustive exploration of this confined domain. In this context, an important observable that characterizes the efficiency of the search process is the cover time, i.e., the minimum time needed by the RW to visit all sites of this domain at least once. The cover time of a single random walker has also an important application in computer science, for instance, for generating random spanning trees (with uniform measure) on an arbitrary connected and undirected graph G.

Research during the past year studied the probability density function (PDF) of the cover time of a finite interval of size L by N independent one-dimensional Brownian motions, each with diffusion constant D. The cover time is the minimum time needed such that each point of the entire interval is visited by at least one of the N walkers. Exact results were derived for the full PDF of cover time for arbitrary N (greater than or equal to 1) for both reflecting and periodic boundary conditions. The PDFs depend explicitly on N and on the boundary conditions. In the limit of large N, it was shown that the cover time approaches its average value of $L^2/(16\ D \ln N)$ with fluctuations vanishing as $1/(\ln N)^2$. Computations of the centered and scaled limiting distributions for large N, for both boundary conditions, showed that they are given by N independent nontrivial scaling functions.
[Satya N. Majumdar, Grégory Schehr and Sanjib Sabhapandit]

Velocity Distribution of Driven Inelastic One-component Maxwell gas

Granular matter, constituted of particles that interact through inelastic collisions, exhibit diverse phenomena such as cluster

formation, jamming, phase separation, pattern formation, and static piles with intricate stress networks. Its ubiquity in nature and in industrial applications makes it important to understand how the macroscopically observed behavior of granular systems arises from the microscopic dynamics. A well-studied macroscopic property is the velocity distribution of a dilute granular gas. While several studies have shown that the inherent nonequilibrium nature of the system, induced by inelasticity, could result in a non-Maxwellian velocity distribution, they fail to pinpoint whether the velocity distribution is universal, and if yes, what its form would be.

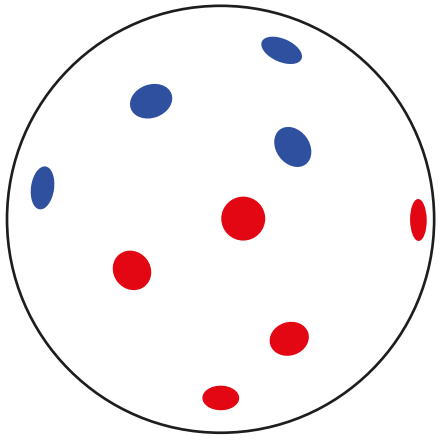
Research during the past year focused on the role of driving in determining the velocity distribution within a simplified model for a granular gas, namely, the inelastic Maxwell model. A simple model of a granular gas described the tails of the steady state velocity distribution of a driven inelastic Maxwell gas where the rate of collision between particles is independent of the separation as well as the relative velocity. It was shown that the steady state velocity distribution is nonuniversal and depends strongly on the nature of driving. The asymptotic behavior of the velocity distribution was shown to be identical to that of a noninteracting model where the collisions between particles are ignored. For diffusive driving, where collisions with the wall are modeled by an additive noise, the tails of the velocity distribution is universal only if the noise distribution decayed faster than exponential.
[Sanjib Sabhapandit, V. V. Prasad, R. Rajesh and Dibyendu Das]

Quantum Information

Entropy and geometry of quantum states

In classical probability theory the question arises of inferring the distribution from a small sample. This arises in drug testing and also in predicting election results. For example, if there are two political parties (say red and blue), by taking a truly random sample of voters one can predict the outcome of an election, if the sample size is large enough. Recent work by TP staff explores related questions in quantum states. Specifically, how does one infer a quantum state by random sampling? The work brings out the subtle nature of quantum information compared to classical information.

The roles of the Bures-Helstrom (BH) and Bogoliubov-Kubo-Mori (BKM) metrics in the subject of quantum information geometry were compared and it was noted that there are two limits involved in state discrimination, called the ``thermodynamic" limit (of N, the number of realizations going to infinity) and the infinitesimal limit (of the separation of states tending to zero). It was shown that these two limits do not commute in the quantum case. Taking the infinitesimal limit first leads to the BH metric and the corresponding Cramer-Rao bound, which are widely accepted in this subject. Taking limits in the opposite order leads to the BKM metric, which resulted in a weaker Cramer-Rao bound. This lack of commutation of limits is a purely quantum phenomenon arising from quantum entanglement. This phenomenon could be exploited to gain a quantum advantage in state discrimination and get around the limitation imposed by the Bures-Helstrom Cramer-Rao (BHCR) bound.
Additionally, a technologically feasible experiment with cold atoms to demonstrate the quantum advantage in the simple case of two qubits was proposed.
[Kumar Shivam, Anirudh Reddy, Joseph Samuel and Supurna Sinha]



The figure represents the geometry of the qubit state space as given by the BKM metric (red ellipses in the lower half) and the BH metric (blue ellipses in the upper half). The figure shows a two dimensional slice of the three-dimensional qubit state space. The geometry is invariant under rotations due to the unitary symmetry of the state space. Note that the ellipticity increases near the boundary of state space. The ellipse on the right shows both BH and BKM metrics superposed. Note that the red BKM ellipse is inside the blue BH ellipse and the blue region represents the quantum advantage.

Quantum Gravity and General Relativity

Gravity, as we all know is a force that attracts a body towards the center of the earth. With Newton's work it became possible to understand gravitational effects with a few simple laws. However, a deeper understanding of gravity only emerged in 1915 with Einstein's theory. The theory of General Relativity explains that the force we perceive as gravity results from the curvature of spacetime (a 4 dimensional entity -3 dimensional space and one dimensional time). An oft-quoted analogy to visualize the curvature of spacetime in the presence of a celestial body is the stretching of a taut rubber sheet around a heavy sphere placed on it. Placing a smaller sphere on this curved region and imparting it with just the right momentum will cause it to revolve around the bigger sphere. The smaller sphere experiences a gravitational pull towards the heavier sphere as a result of the curvature of the rubber sheet. On the other hand we have the standard model which explains basically everything else in terms of the three forces-electromagnetic (the force that

governs the attraction and repulsion of charged particles like electrons), the strong force (the force that keeps the nucleus from falling apart) and the weak force (responsible for radioactive decay). The Standard model and General Relativity are two theories that explain the known world. Unfortunately, owing to their incompatibility, merging the two theories is a very difficult task. In fact, the Holy Grail for many physicists is to merge these two theories into a Theory Of Everything. The incompatibility can be traced to the origin of the fundamental forces. In the standard model systems interact via quantum particles or force carriers and evolve within a background spacetime structure whereas in General Relativity curvature of spacetime is the origin of gravity. The fabric of spacetime acts both as the background structure for gravitational interactions as well as a dynamic phenomenon, giving rise to this interaction.

Loop Quantum gravity (LQG) overcomes this incompatibility by generalizing 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.

Another approach to overcome the incompatibility is Causal Set Theory (CST). CST is built on two basic postulates (i) spacetime is discrete, made of indivisible units or quanta, and that (ii) Causal structure contains geometric information: knowledge of events that are causally connected to other events. The combination of the above two leads to the idea of a causal set as a fundamental structure of spacetime.

In the past year researchers at RRI have furthered our knowledgebase in both the above avenues of research in quantum gravity.

Boundaries and corner terms in the action for General Relativity

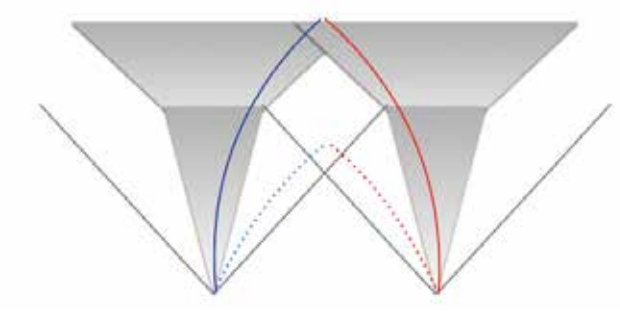
During the past year, theorists at the Institute revisited the action principle for General Relativity motivated by the path integral approach to quantum gravity. The work deals with the action principle for General Relativity. From the beginning of the subject it was realized that boundaries are very important in the proper variational principle for Relativity. The work views this question motivated by the path integral approach to quantum gravity. The study gives the forms of the boundary terms and also the corner terms that appear when the boundary has discontinuities.

A spacetime region whose boundary has piecewise C2 components, each of which can be spacelike, timelike or null was considered along with metric variations in which only the pullback of the metric to the boundary is held fixed. Allowing all such metric variations, a unified treatment of the spacelike, timelike and null boundary components was developed using Cartan's tetrad formalism. Apart from its computational simplicity, this formalism gave a simple way of identifying corner terms. They also discussed "creases" which occur when the boundary is the event horizon of a black hole. Such a treatment is geometric and intrinsic and the results were presented both in the computationally simpler tetrad formalism as well as the more familiar metric formalism. Additionally, known results from a simpler and more general point of view were recovered along with some new ones.
[Ian Jubb, Joseph Samuel, Rafael Sorkin and Sumati Surya]

Echoes of Asymptotic Silence in Causal Set Quantum Gravity

Recent RRI research explored the idea of asymptotic silence in causal set theory and found that causal sets approximated by continuum spacetimes exhibit behavior akin to asymptotic silence. Using an intrinsic definition of spatial distance between causal set elements in the discrete analogue of a spatial hypersurface along with numerical simulations for causal sets approximated by D=2,3 and 4 dimensional Minkowski spacetime, it was shown that while the discrete distance rapidly converges to the continuum distance at a scale roughly an order of magnitude larger than the discreteness scale, it is significantly larger on small scales. This allowed definition of an effective dimension, which exhibits dimensional reduction in the ultraviolet, while monotonically increasing to the continuum dimension with increasing continuum distance. These findings were interpreted as manifestations of asymptotic silence in causal set theory.

[Astrid Eichhorn, Sebastian Mizera and Sumati Surya]



In causal set theory spacetime is assumed to be atomic. The only continuum information which is retained is that contained in the causal relations between spacetime events. In this picture we depict how light cones can be effectively narrower in the ultraviolet in continuum-like causal sets. This "asymptotic silence" seems to be a universal feature of several discrete approaches to quantum gravity.

The Large N limit in 2D Causal Set Quantum Gravity

Past research by RRI staff had shown that 2D causal set quantum gravity exhibits a remarkable phase transition from a continuum phase to a crystalline non-continuum phase. It was also shown that this phase transition could play a non-trivial role in determining the Hartle-Hawking ground state. Much of the analysis, however, was done for a fixed system size and the lingering question was whether the effect is due to the finite size of the system.

During 2016-17, using the RRI HPC cluster, this phase transition has been analyzed in great detail for a wide range of system sizes and coupling constants. It was found that it shares some features with a first order phase transition for a large range of values of the coupling constant. Analysis of the scaling behavior showed that a rescaling of the temperature with the system size leads to a well-behaved collapse indicating that the phase transition survives the large N limit. In fact it has been possible to make very good scale invariant fits to the data for the averaged action, and the work led to the deduction that for finite temperature, the continuum phase corresponds to anti de Sitter spacetime.
[Lisa Glaser, Denjoe O'Connor and Sumati Surya]

Propagation in polymer parameterized field theory

The Hamiltonian constraint operator in Loop Quantum Gravity acts ultralocally. Smolin has argued that this ultralocality seems incompatible with the existence of a quantum dynamics, which propagates perturbations between macroscopically separated regions of quantum geometry. RRI theorists presented evidence to the contrary within an LQG type `polymer' quantization of two-dimensional Parameterized Field Theory (PFT). PFT is a generally covariant reformulation of free field propagation on flat spacetime.

It was shown explicitly that while, as in LQG, the Hamiltonian constraint operator in PFT acts ultralocally, states in the joint kernel of the Hamiltonian and diffeomorphism constraints of PFT necessarily describe propagation effects. The particular structure of the finite triangulation Hamiltonian constraint operator plays a crucial role, as does the necessity of imposing (the continuum limit of) its kinematic adjoint as a constraint. Propagation is seen as a property encoded by physical states in the kernel of the constraints rather than that of repeated actions of the finite triangulation Hamiltonian constraint on kinematic states. The analysis yielded robust structural lessons for putative constructions of the Hamiltonian constraint in LQG for which ultralocal action co-exists with a description of propagation effects by physical states.
[Madhavan Varadarajan]

Weak Coupling limit of Euclidean Gravity – Propagation

The lessons learnt from past research at the Institute on Parameterised Field Theory were incorporated during the year into the definition of the quantum dynamics of a weak coupling limit of Euclidean gravity. The aim of this work was to demonstrate, for the first time, that ultralocality of the Hamiltonian constraint action in the gravitational setting of the model is compatible with propagation affects.
[Madhavan Varadarajan]

Weak Coupling limit of Euclidean Gravity: Anomaly free quantum dynamics - Multiple constraint action

Current research efforts are geared towards building on the structures that were introduced a few years ago in an attempt to define a satisfactory domain of off-shell states which support an anomaly-free representation of the algebra of quantum constraints for Smolin's novel weak coupling limit of Euclidean Gravity.
[Madhavan Varadarajan]

Quantum transport in mesoscopic systems

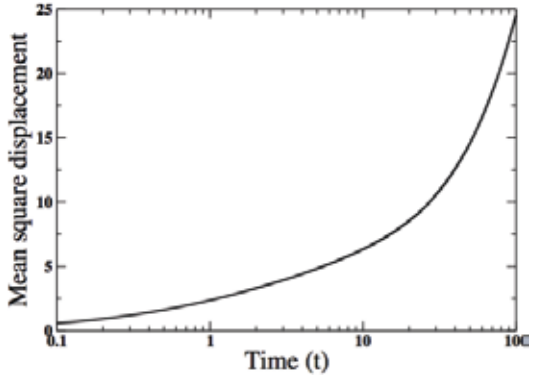
A dust particle suspended in a fluid will undergo random motion (diffusion) as a result of collisions with a number of atoms or molecules that make up the fluid, whose motion in turn is due to thermal fluctuations. Thermal fluctuations are nothing but the jiggling and wiggling of atoms and molecules, which manifests as temperature of the fluid. Lower the jiggling and wiggling less is the temperature and vice versa. What happens when we lower the temperature of the system and scale down the size of the particle until we reach a regime where thermal fluctuations are negligibly small and the diffusion is driven primarily by zero point fluctuations, purely of quantum origin? Research during 2016-17 has attempted to answer this question as discussed below.

Quantum Diffusion

Brownian motion is one of the cornerstones of nonequilibrium statistical mechanics. The relevant equation for studying Brownian motion is the Langevin equation; it contains frictional forces and random forces. The fluctuation dissipation theorem relates these forces to each other. A Brownian particle suspended in a liquid subjected to thermal fluctuations undergoes diffusion. In classical theory, the Smoluchowski-Einstein relation relates the diffusion constant to the frictional coefficient. There have been many efforts to understand the influence of quantum zero point fluctuations on the motion of a quantum particle coupled to a heat bath. In these works, certain assumptions were made about the nature of the heat bath in which the particle moves and the type of coupling

between the particle and the heat bath. Using these system-bath models a logarithmic law of diffusion was obtained at low temperatures. Recently there has been an analysis of the random motion of a mirror in a thermal bath where zero temperature diffusion effects were studied. In contrast to this, RRI theorists along with collaborators have adopted an approach that is straightforward and very general and depends neither on the specific composition of the heat bath nor on the strength of the coupling between the bath and the particle.

Diffusion at low temperatures was analyzed by bringing the fluctuation-dissipation theorem to bear on a response-function which, given current technology, can be realized in a laboratory with ultra-cold atoms. As with earlier analysis, the new response function also led to a logarithmic diffusion law in the quantum domain, indicating that this behavior is robust. The new response function has the additional advantage of yielding a positive mean square displacement even in the regime of ultrashort times, and more generally of complying with both ``Wightman positivity'' and ``passivity'', whose interrelationship was also studied.
[Urbashi Satpathi, Supurna Sinha, and Rafael Sorkin]



Plot of the mean square displacement as a function of time (in logarithmic scale) in arbitrary units. It depicts the diffusion behaviour at time-temperature ranges spanning between the very low temperature quantum regime to the high temperature classical regime.

Quantum Mechanical scattering phase shifts in mesoscopic systems

Since the experimental observation of quantum mechanical scattering phase shift in mesoscopic systems, several aspects of it have not yet been understood. The experimental observations have also accentuated many theoretical problems related to Friedel sum rule and negativity of partial density of states. Theorists at the Institute along with collaborators addressed these problems using the concepts of Argand diagram and Burgers circuit. The possibility of negative partial density of states in mesoscopic systems can now be proven. Such conclusive and general evidence cannot be given in one, two or three dimensions. The work showed a general connection between phase drops and exactness of semi classical Friedel sum rule. It also showed that the Argand diagram for a scattering matrix element can be of few classes based on their topology, and all observations can be classified accordingly.
[Urbashi Satpathi and P. Singha Deo]

Nonlinear Quantum Optics

The optical response of a material scales linearly to the electric field of incident radiation. However, when the intensity of the incoming radiation (in other words the amplitude of the electric field) is sufficiently high, the material can respond nonlinearly. The study of the interaction of intense light with matter is the subject of nonlinear optics. Nonlinear quantum optics is a relatively new field to specifically investigate nonlinear light-matter interaction in the quantum regime with few photons. A detailed description of the research undertaken in this area at RRI, during 2016-17, is given below

Critical features of nonlinear optical isolators for improved nonreciprocity

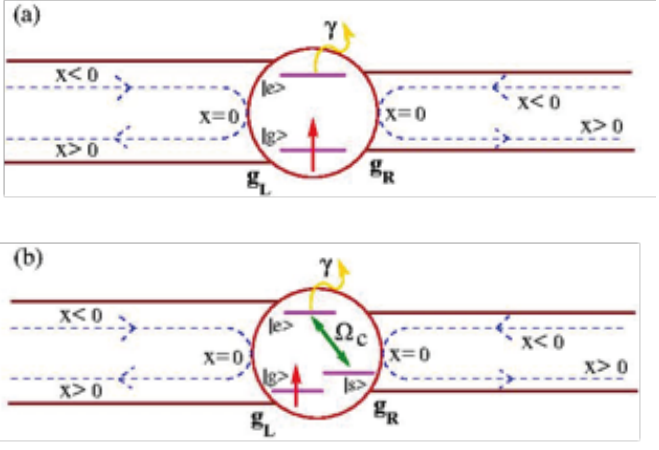
Light propagation in a nonlinear optical medium is nonreciprocal for spatially asymmetric linear permittivity. The physical mechanisms and properties of such nonreciprocity (NR) were examined by calculating transmission of light through two models of a nonlinear optical isolator consisting of (a) a two-level atom and (b) a driven Λ-type three-level atom coupled asymmetrically to light inside open waveguides (see Figure). A higher NR was observed in the model (b) than in the model (a) due to a stronger optical nonlinearity in the former. The critical intensity of incident light for maximum NR was determined along with a dependence of the corresponding NR on asymmetry in the coupling. Surprisingly, it was found that it is mainly coherent elastic scattering compared to incoherent scattering of incident light that causes maximum NR near the critical intensity. A higher NR of an incident light was observed in the presence of an additional weak light at the opposite port.

An optical isolator or diode creates nonreciprocal transmission of light, which implies a difference in light transmission under reversal of incoming light's direction. An optical isolator is an essential component in optics laboratories and optical communication circuits. It is typically used to prevent unwanted feedbacks such as to protect a laser source or an antenna from reflected noises. Generally, these devices are made of magneto-optical materials, which have an asymmetric permittivity tensor. However, magnets are averse to on-chip integration, and magnetic fields are pernicious to delicate superconducting devices which can also be part of the optical circuits. Therefore, optical isolators without magnetic materials have attracted great interest in recent years.

Research undertaken at the Institute in previous years resulted in a proposal for a nonlinear optical isolator whose operation

was based on optical nonlinearity and spatially asymmetric linear permittivity. This mechanism for nonreciprocal light propagation has been further investigated in many recent studies. The proposed device can be realized in experiments with superconducting transmission lines coupled to superconducting qubits, or line-defects in photonic crystals coupled to quantum dots. However, some significant modifications in the original calculation were required for an adequate description of these experimental systems. These were (i) incident light in coherent states instead of in Fock states and (ii) incorporation of pure-dephasing and non-radiative photon loss from the atom either of which is inevitable in such physical systems. During 2016-17, RRI staff has applied quantum Langevin equations and Green's function (LEGF) method to address these tasks.

The following two physical mechanisms were also proposed to improve nonreciprocity: (i) by having higher optical nonlinearity in the model of a nonlinear optical isolator and (ii) in the presence of backward propagating noise whose spectrum has overlap with the incident forward beam. While mechanism (i) would be easy to implement with model (b), mechanism (ii) would be practical in many situations where optical isolators are used.
[Dibyendu Roy]



Models for a nonlinear optical isolator. (a) A two-level atom and (b) a driven Λ-type three-level atom are coupled asymmetrically to light inside open waveguides. A real-space description of the propagating photons is shown by dashed lines where the photons at $x < 0$ and $x > 0$ represent, respectively, incoming and scattered parts on each side of the atoms. The photons at $x = 0$ are coupled to the atomic transition between $|g\rangle$ and $|e\rangle$.

Exact method to study light propagation through nonlinear quantum media

An exact method to investigate propagation of a laser light through optically nonlinear quantum media of atoms has been developed by staff at the Institute. The method employed a matrix product operator description to write and solve a large set of quantum Langevin equations of atomic operators obtained after integrating out the light fields. This method was applied in one-dimensional atomic media modeled microscopically as a transverse-field Ising chain and a Heisenberg spin chain with nearest-neighbor coupling for both ordered and disordered atomic media. The single-photon transmission in these systems is coherent and can be Anderson localized in the presence of disorder. The roles of optical nonlinearity or effective photon-photon interaction on multi-photon transmission in such ordered and disordered media were investigated. Studies were undertaken to understand how various losses and long-range coupling between atoms can alter single- and multi-photon transmission in these media. This enabled evaluation of atomic correlations to investigate nonequilibrium phase transitions in a nonlinear atomic medium driven by light field.

Earlier research at the Institute resulted in a theoretical method based on quantum Langevin equations and Green's function (LEGF) to study nonequilibrium quantum transport across a system connected to baths at the boundaries. This method was a generalization of the Heisenberg-Langevin equation approach to nonequilibrium when the baths at the boundaries of the system are kept at different temperatures or chemical potentials or magnetizations. Quantum LEGF method leads to expressions like those of the nonequilibrium Green's function (NEGF) for transport coefficients. It also reproduces the results of the Landauer-Buttiker formalism in particular limits. Previously the quantum LEGF method was applied for investigating nonequilibrium transport in various noninteracting and mean-field interacting open quantum systems of electrons and phonons.

Recent work during 2016-17 has extended the application of quantum LEGF method to study nonlinear light propagation through various one-dimensional models of atom-photon systems. In this sense, it was an extension of the previous research theme. However, it required a sophisticated numerical calculation using matrix product operators, which enabled calculations of transmission and reflection of a laser light in the coherent state from different nonlinear optical media as well as derivations of correlation properties of atoms driven by the laser field.
[Dibyendu Roy and Pooja Manasi Srinivas]

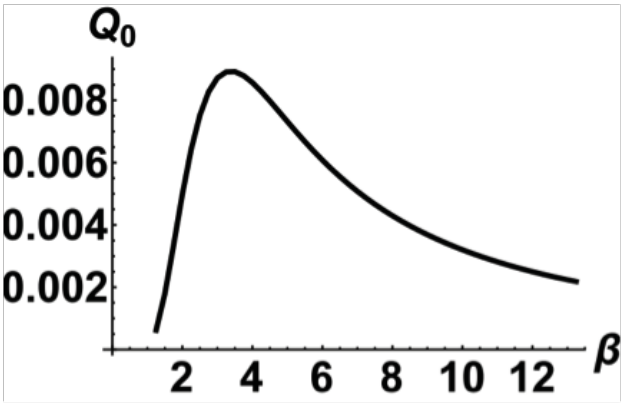
Polymer Physics (Semi flexible polymers, Biophysics)

A polymer is a large molecule that consists of repeating subunits and can be thought of as a chain of identical molecules connected end to end. If the repeating subunit is a biological entity then it is a biological polymer. These polymers exist as linear chains or they can loop around to form rings. Loop formation plays a crucial biological function in many biological semi-flexible polymers. For example, in a

DNA (Deoxyribonucleic acid, the storehouse of genetic biological information) molecule, distant parts of the molecule need to come together to form a loop for certain gene regulation processes to get initiated. More recently, there have been experiments studying loop formation in the biopolymer actin. Actin plays a critical role in many cellular functions including cell mobility, shape and muscle contraction. In general, bending (for example leading to loop formation) and torsional (leading to twisting) properties of biological polymers can directly influence numerous cellular processes. For all these reasons, it is important to study the mechanical properties of biological polymers by performing theoretical analysis followed by experimental verification.

Ring Closure in Actin polymers

During 2016-17, TP staff and collaborators undertook an analysis for the ring closure probability of semi-flexible polymers within the pure bend Worm Like Chain (WLC) model. The ring closure probability predicted from the analysis can be tested against fluorescent actin cyclization experiments. The study also included the effect of ring closure on bend-angle fluctuations in actin polymers.
[Supurna Sinha and Sebanti Chattopadhyay]



A plot of the ring closure probability density in physical space versus the scaled contour length of a biopolymer. The function is small for very large and small values of the scaled contour length and peaks around an intermediate value of about 3.

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 the Monthly Notices of the Royal Astronomical Society, Astrophysical Journal, Astronomical Journal, Astroparticle Physics, New Astronomy, Astronomy and Astrophysics, Journal of Cosmology and Astroparticle Physics, Journal of Astrophysics and Astronomy, Publications of the Astronomical Society of Australia and Physical Review.

The Soft Condensed Matter group has its work published in Chemistry Select, Colloids and Surfaces, Electrochimica Acta, Faraday Discussions, Liquid Crystals, Soft Matter, Analytical Letters, Ionics, Physical Review, RSC Advances, Journal of Luminiscence, Journal of Thermal Analysis and Calorimetry, Journal of Cell Biology, Tetrahedron, Thermochimica Acta, Journal of Colloids and Interface science, Journal of Molecular Liquids, Journal of Molecular Structure, Physical Chemistry Chemical Physics and Rheologica Acta.

Publications of the Light and Matter Physics group can be found in Scientific Reports, Physical Review, Physical Review Letters, Applied Physics, Carbon, Ceramics International, Journal of Optical Society of America, Applied Physics Letters, International Journal of Quantum Information, Journal of Applied Physics, Journal of Alloys and Compounds, Journal of Modern Optics, Journal of Materials Chemistry, Journal of Optics, Journal of Materials Science: Materials in Electronics, Optical Materials, Optics Communications, Optics Express, Plasmonics, Physics of Plasmas and Materials Science and Engineering.

Theoretical physicists at RRI use journals like Annals of Physics, Physical Review, Physics Letters A, Review of Modern Physics, Classical and Quantum Gravity, Europhysics Letters, Polymer Journal 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 2016-2017. There were 8 publications in conference proceedings and 26 publications (23 in journals and 3 in conference proceedings) are in press.

Members of the Institute also regularly publish books and/or articles for popular science magazines to reach out to a wider audience beyond that of specialized technical and scientific journals. During the past year, RRI members wrote 1 book and 2 book chapters. 4 popular science articles were published in the journals Astronomers Telegram, Current Science and Resonance.

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

Extramural Grants, Awards and Fellowships

Extramural Grants

1	**Biswajit Paul**	*ISRO grant for POLIX* "X-ray Polarimeter experiment (POLIX) Engineering Model".Grant money received - Rs. 44,48,000 from ISRO for development during FY 2015-16. Funding request for Rs 9,50,00,000 for POLIX payload over the duration of the project has been approved. MOU between RRI and ISRO is pending.
2	**Sadiq Rangwala**	*CEFIPRA proposal 5404* LORIC - LOng Range Interaction in ultraCold gases. Co-PI - Olivier Dulieu (Laboratoire Aime Cotton, France). Total grant money Euro 279,400, of which RRI component is INR 90,89,135. Project Duration: March 2016 - February 2019.
3	**Sanjib Sabhapandit**	*CEFIPRA/Indo-French grant* "Extreme events and large deviations in strongly correlated many body systems." Co-PI's - Abhishek Dhar (ICTS, TIFR), Gregory Schehr (LPTMS, Orsay). Total grant Money: Rs 33,99,336, RRI share: 6,92,332 Project Duration: December 2016 – November 2019
4	**Urbasi Sinha**	*Templeton grant awarded by John Templeton Foundation* Project Name - Unveiling the Nature of quantum reality: A theoretical and experimental approach employing non destructive weak measurements. Co-PI - Alexandr Matzkin(CNRS, France). Grant amount - 77, 880 Euro. Grant released - 70,902 Euro. Grant period - November 2015 - October 2018.
5	**Biman Nath**	*Indo-Israel grant No. 504/14* Title: "Galactic outflows and the sky's biggest shock". PI - Prateek Sharma, IISc. Commenced in 2014. Duration 4 years. Total amount for the Indian side is Rs 86 lakhs.
6	**Sumati Surya**	*Foundational Questions Institute (FQXI) Fund* Proposal Title: "Quantum Dynamics of Causal Sets" September 2014 – August 2018 Sanctioned: $58000, Spent so far: $51,317

Fellowships

1	**Dibyendu Roy**	*SERB-Ramanujan Fellowship* Received the Ramanujan Fellowship in November, 2015. This fellowship is for five years.
2	**Sourav Dutta**	*DST Inspire Faculty Award* Fellowship commenced in April 2015. Duration 5 years.
3	**Sumati Surya**	*Emmy Noether Fellowship by Perimeter Institute, Waterloo, Canada* For April 2017-September 2017 and April 2018-September 2018. Full financial support towards visits to Perimeter Institute, Waterloo, Canada, for the above periods.
4	**Gautam Soni**	*DBT- Ramalingaswami Fellowship* Project title - Epigenetic gene sequencing by chromatin condensation using nanodevices. Fellowship started in January 2014. Duration 5 years.
5	**Nayantara Gupta**	*DAAD fellowship* Awarded DAAD fellowship in February, 2017 for professional collaborative visit to Germany for two months.
6	**Kartick Chandra Sarkar**	*KITP fellowship* Graduate fellowship program at the Kavli Institute for Theoretical Physics, Santa Barbara, USA. Duration: January 2017 to July 2017.

Sanjukta Roy's outstanding reviewer award

IOP publishing has recognized Sanjukta Roy as an "outstanding reviewer" for the Journal of Physics B: Atomic, Molecular and Optical Physics in 2016. The recognition is for her invaluable service in "upholding the quality and integrity of IOP publishing".

Hema Ramachandran's excellent rating on her CEFIPRA project

Hema Ramachandran and her group consisting of Sriram Sudarsanam, James Mathew, Meena M.S. and their French counterparts Mehdi Alouini, Swapnesh Panigrahi and Julien Fade (all from Universite de Rennes, France) have received excellent rating for their project "Real-time imaging through fog over long distances". CEFIPRA is an Indo-French funding initiative that awards research grants to collaborative research proposals between the two countries on cutting edge science and technology projects.

SASTRA-G.N. Ramachandran award for Prof N. Kumar

This past year, SASTRA University conferred the SASTRA-G.N. Ramachandran award for excellence in physics on Prof N. Kumar.

Best Stall Award at India International Science Festival 2016 for RRI

RRI, represented by Naresh V.S., Debarshini C. and Sarabagopalan G., received the best stall award at the 2nd India International Science Festival held at CSIR-National Physical Laboratory, New Delhi during 7–11 December 2016. The stall was modelled on our iconic RRI main building.

Research Facilities

The Research Facilities of the Institute is in five sections – the Electronics Engineering Group, the Soft Condensed Matter Group Labs, the Mechanical Engineering Section, the Library and the Computer Section. They are aimed at providing specialized services to the various research projects undertaken in the Institute.

Electronics Engineering Group:

Electronics Engineering Group or EEG is a dedicated team of electronics engineers and technical personnel capable of designing and developing state of the art electronic systems for conducting research in experimental projects in various fields of basic science. The main strength of EEG is in experimental design and purpose building of specialized receiver systems for radio astronomy. RRI has a long history of having developed a variety of analog and digital systems (receivers, spectrometers, correlators) for enhancing the capabilities of national and international telescope facilities, thus enabling new science. The group has designed and built broadband antennas, low-noise front end receiver systems and high dynamic range backend receivers based on FPGAs, for radio telescopes operating at from decameter to millimetre wavelengths. EEG is equipped with modern instruments for the measurement and testing for analog and digital electronic systems. It has fabrication and testing facilities for RF systems, a PCB engraver for pcb fabrication, and modern EM simulation and CAD design packages for the development of antenna and FPGA systems.

The Electronics Engineering Group works along with other RRI members on various on-going experimental projects of the Institute like i) SARAS 2, ii) APSERa, iii) Brain Computer Interface, iv) SWAN, v) X-Ray Polarimeter, vi) Single-atom trap experiment, vii) Microwave kappa experiment, viii) SteP, and ix) physics experiments in soft matter. They are briefly described below.

1. Receiver System for SARAS 2

Somashekar, Raghunathan, Girish, Srivani, Kasturi, Madhavi, Kamini (EEG staff), Udaya Shankar, Ravi Subrahmanyan (PI)

SARAS 2 is an improved version of SARAS – a dedicated instrument built to precisely measure the cosmic radio background and faint features in the sky spectrum at longer wavelengths (7.5 – 1.2 m). EEG has built a compact low-noise and broad band analog front end receiver for this instrument. A spherical monopole antenna (Ref. Fig. 2) operating in the non-resonant mode in the frequency range 40-200 MHz forms the detector element in this receiver system. The detector output is split into two and is passed through two identical chains of receiver electronics configured in the correlation mode. They are digitized further using high speed analog to digital converters and processed in Virtex-6 FPGA based correlation spectrometer to produce the spectrum of the sky signal. Phase switching mechanism is incorporated in the receiver system to minimize the effects of systematics generated within the receiver system. Single mode optical fibers are used in the RF chain to get 60-70 dB reverse isolation. Three banks of rechargeable Lithium-ion batteries are used for powering the front-end electronics.

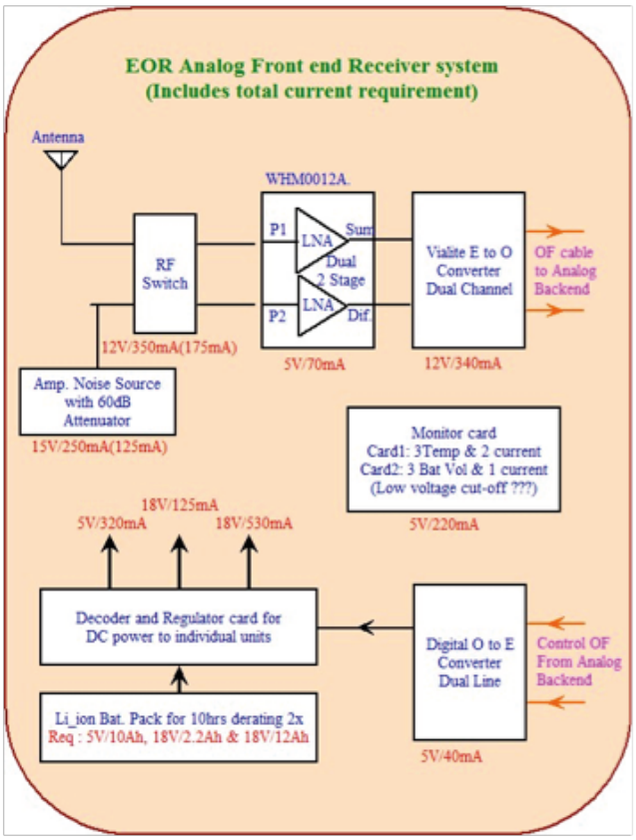


Fig. 1. Front End receiver of Saras 2 – an instrument custom built to detect the global EoR signal.

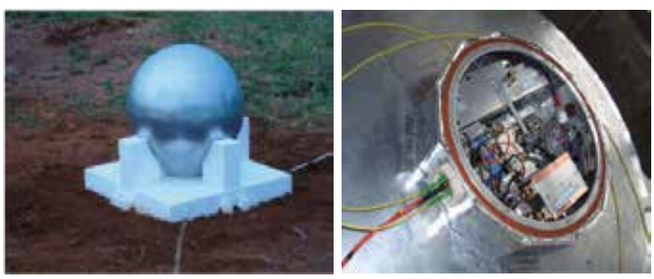


Fig. 2. (Top) Spherical monopole antenna designed to work in the frequency range 40–200 MHz. (Bottom) Front-end electronics housed below the antenna.

2. Receiver System for APSERa

Somashekar, Raghunathan, Girish, Srivani, Kasturi, Madhavi, Kamini (EEG staff), Udaya Shankar, Ravi Subrahmanyan (PI)

The Array of Precision Spectrometers for the Epoch of RecombinAtion – APSERa – is a more futuristic project to detect recombination lines from the Epoch of Cosmological Recombination in the spectrum of the radio sky in the 2-6 GHz range. A correlation type receiver system with an analog bandwidth of 2 GHz is being built by EEG for this scientific experiment. As part of it, a frequency independent planar dipole antenna (Ref. Fig. 3 & 4) as a detector element has been designed to operate in the frequency range 2-4 GHz with smooth spectral characteristics and very low side lobe level (< 30 dB).

Fig. 3. Planar dipole antenna designed for the band 2-4 GHz.

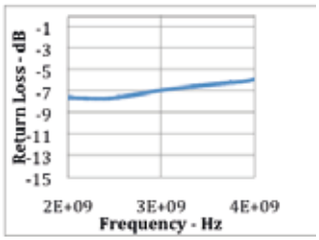


Fig. 4. Spectral return loss measurement of the antenna.

The digital spectrometer is built around a high-speed digital signal processing platform consisting of time-interleaved, multi Gigasamples per second analog-to-digital converters (ADC) and a Virtex-6 FPGA. The spectrometer outputs are averaged to get self-power and a cross-power spectra with 512 spectral channels across the sampled bandwidth. To reduce the level of spurious contents in the output spectrum, a calibration scheme have been developed to minimize the DC offset and gain mismatch across the individual ADC cores of the time-interleaved ADC. Currently, the spectrometer is being integrated with other sub-systems of the receiver chain and tested for performance.

3. Brain Computer Interface

Sujatha (EEG), Hema Ramachandran (PI), B. Ramesh, G. Rameshwara, Mohammed Ibrahim

Brain Computer Interface (BCI) system, being developed completely inhouse at EEG, aims at helping physically impaired patients. The system has been designed to respond to brain signals of the user and help them perform their desired actions, without any physical movement. The block diagram of the system is shown in Fig. 5. The physically impaired user is subjected to various LED based stimuli which are mapped to different actions. These give rise to the "visually evoked potentials". The user concentrates on the stimulus of interest. The electro-encephalogram of the subject is constantly monitored and the particular stimulus that is evoking the strongest potential is determined and the corresponding action initiated. Thus, devices can be operated based on intent of action determined from brain signals, without any physical movement.

The challenges are to make the system i) work reliably with robustness, ii) user-friendly and iii) error free. It also requires adaptive measures to correct for i) user to user variation in their response to the stimuli, and ii) fatigue induced reduction of signal, while simultaneously minimizing the time required to extract the signal.

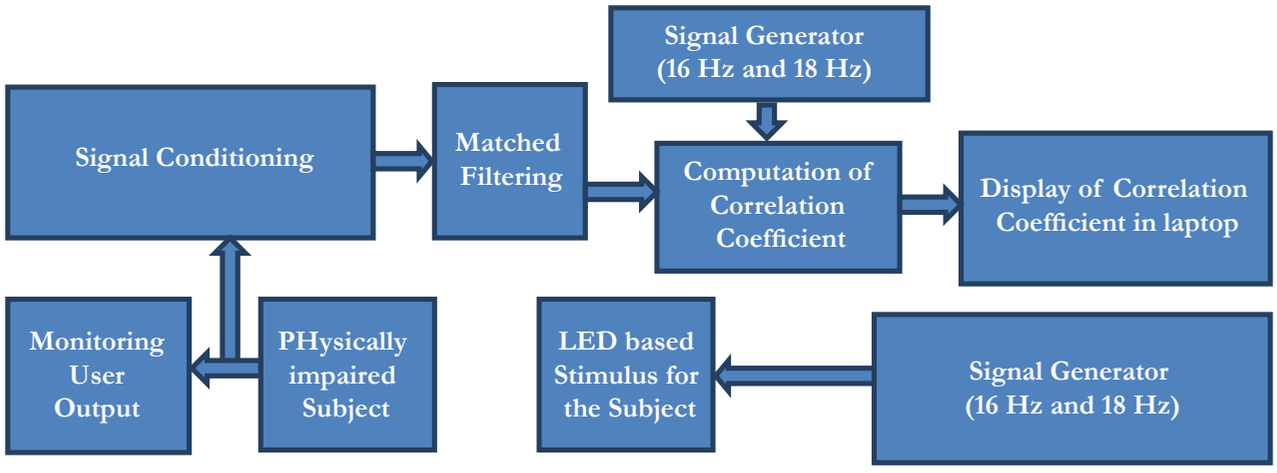


Fig. 5 Brain Computer Interface system

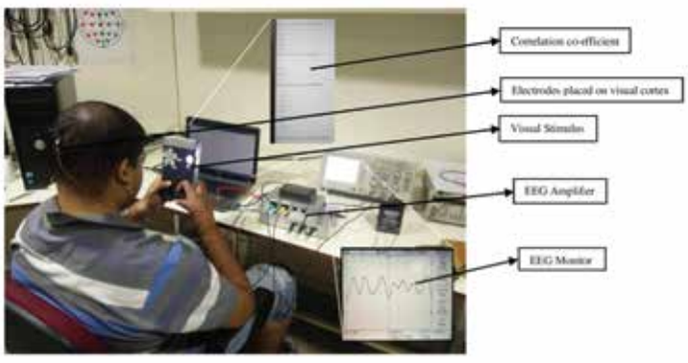


Fig. 6. Brain Computer Interface System

Sujatha of EEG has been working with Hema Ramachandran and B. Ramesh, helping to i) arrive at the right configuration of LED based stimuli, ii) validate the methodology developed on a couple of subjects, and iii) develop monitoring system to continuously monitor the EEG signals of the subject. The system has been made standalone, compact and portable by powering it through batteries and operating it through a touch-sensitive front panel. It is now ready for trial on volunteers. The experimental setup of BCI is shown in Fig. 6

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4.Receiver System for SWAN

Raghavendra, Vinutha, Srivani, Nagaraj, Kamini, Arasi, Deshpande (PI) SWAN is an initiative at RRI to design and develop a broad-band Sky Watch Array Network (SWAN) across India for radio astronomy, over the frequency band 50-500 MHz. The main objectives of SWAN are to i) conduct searches and studies of fast transients and ii) facilitate high-angular-resolution imaging, while enabling active participation of students from educational institututions/universities across India in all aspects of SWAN. For this activity both narrowband and broad band receivers are being developed.

SWAN Narrow band receiver system

The narrow band receiver system uses eight tile antennas similar to those used by RRI in its international collaboration Murchison Widefield Array (MWA). Each MWA tile is an array of 16 dipoles arranged in square grid of 4x4. The outputs of all the 16 dipoles are amplified and combined together with appropriate phases in a beamformer. The beamformer output is downconverted to 140 MHz IF using a Rb disciplined local oscillator and digitized and processed in a computer for off line analysis. The block diagram is shown in Fig. 7. Eight MWA tiles are equipped with eight such receiver systems to form one SWAN 8-station tied-array system with a common frequency standard.

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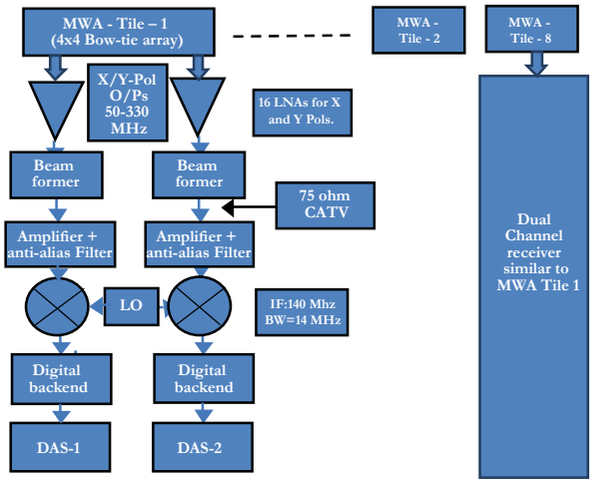


Fig. 7(a). Block diagram of Narrow band Receiver system.

Each of the SWAN-8 tiles has been refurbished with relevant new replacements. This process involved the following major effort :

Several of the RF low noise amplifiers (80-330 MHz), which are a part of each bow-tie antenna element, that were damaged due to lightning, were identified and rectified. Interestingly, the points of failure were not same in all cases.

i. Most of the original RF cables, of equal lengths, connecting each antenna element to the beamformer input were found to be seriously damaged due to weathering, needing immediate replacement and protection from future weathering damage. Such RF cables were replaced by new ones, having same dielectric constant, electrical and RF characteristics as the original ones, and are now protected using plastic-tube guides.

ii. The beamformed RF output signal from each of the beamformers associated with each of the 8 tiles are carried all the way to the receiver room through a 75 ohm CATV cable, where the 80-330 MHz spectrum signal is connected to the existing GBT-RRI narrow band receiver through an impedance conversion device for further processing. These cables, which connect the beamformer RF output connector to the receiver system were replaced by new similar cables with sturdy connectors for reliability.

iii. A beamformer unit (placed close to the tile so as to save on overall cable lengths), combines a set of inputs received from 16 array elements in a tile after introducing programmable relative delays (through computer-control), and provides a single output per polarization. At present, all beamformer controls are derived from a common parallel-port of one PC.

As a result of the above refurbishment of the tiles and its interconnectivity, the RF signals are now reliably configured, and are being routinely processed through the MBR narrow-band receiver system, having instantaneous bandwidth of 16 MHz, for astronomical observations, and interferometer measurements are being conducted using a software correlator developed inhouse.

SWAN Broad-band Receiver System

A broad-band receiver system is being developed to operate in the frequency range 50-400 MHz. It has a low noise amplifier, a high gain amplifier module, a set of shaping filters and a digital receiver system. The RF band of 50-400 MHz of the antenna is split into two sub-bands of 175MHz and are fed to two identical chains of backend receivers. Each of them is digitized independently by ADCs. The digital receiver system being developed based on ViQuad board is capable of digitizing simultaneously eight input signals of 175 MHz band. The evaluation of the digital receiver system is in progress. The mechanical sub-systems to house the Digital Electronics are being designed.

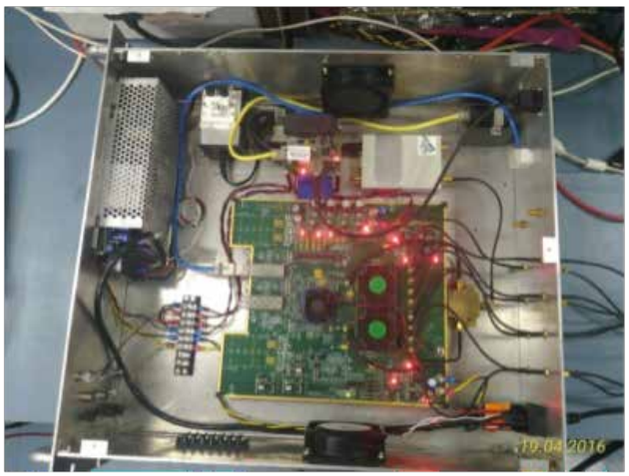


Fig. 7(b). Prototype broadband digital system for SWAN

Portable dual receiver

Portable Dual Receiver is a complete receiver system built by EEG for i) providing hands-on experience to students and conduct observations using various telescopes. The receiver system is capable of processing RF data anywhere in the frequency band of 100-1000 MHz over a bandwidth of 14 MHz. The receiver is portable and thus this feature enables any user to carry it from place to place easily. After basic receiver setup was achieved desirably for the compact portable version, the finer issues like potential LO-leakage and ground loops were addressed carefully, and were overcome by housing the Analog front-end and Digital back-end receivers in two separate boxes and also with proper grounding channels. This receiver, and particularly its portability, made possible use of ST-Radar arrays, which have recently been commissioned at CUSAT-Kochi and ARIES-Nainital for wind profiling, to conduct test observations in the direction of a few bright astronomical sources (in collaboration with teams at the two institutes and with Sarabagopalan from EEG participating in tests at CUSAT).

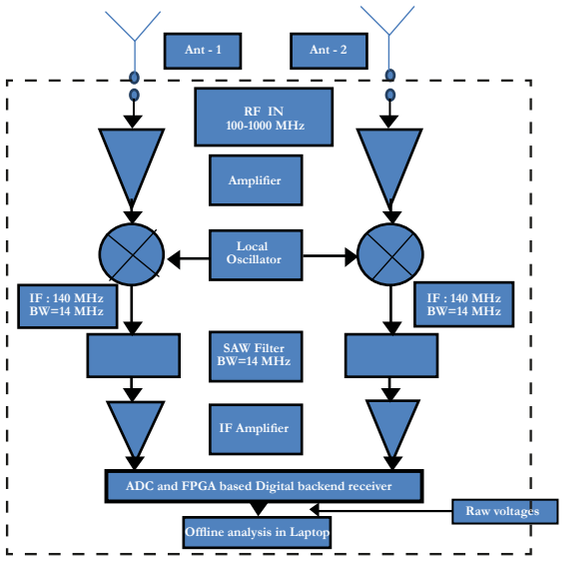


Fig. 8. Block diagram of a Portable dual receiver

5. Thomson X-ray Polarimeter – POLIX – for measurement of X-ray Polarization of cosmic sources

Rishin P.V., Gopala Krishna M.R., Sandhya P., Mamatha T.S., Arasi Sathyamurthy, Nagaraja H.N (EEG Staff), Biswajit Paul (PI), Pooja Verma, G. Rajagopala, Nirmal Iyer, Varun, Mohammed Ibrahim and Abhilash Kulkarni

POLIX is an X-ray polarimeter being designed and developed at RRI which has been approved for a dedicated small satellite mission of ISRO named XPoSat. The instrument is based on Thomson scattering and works in energy band of 5-30 keV.

The mechanical configuration of the polarimeter consists of four X-ray detectors, placed cyclic symmetrically on all four sides of a scattering element. X-rays from cosmic sources are allowed to fall on the scatterer through a collimator which restricts the field of view of the instrument. Currently, the instrument development for most payload subsystems are in the Engineering model phase and tests towards Engineering model qualification are in progress.

On the detector front, we have successfully carried out vibration test on one detector. The detector was vibrated in the frequency range and acceleration levels specified by ISRO Enviromental Test Level Specifications (ETLS), and no resonance was observed in the required frequency range. The detector survived the test without any damage to the mechanical structure or the wires, thereby validating the mechanical design. Figure shows the detector undergoing vibration test on the mechanical shaker.

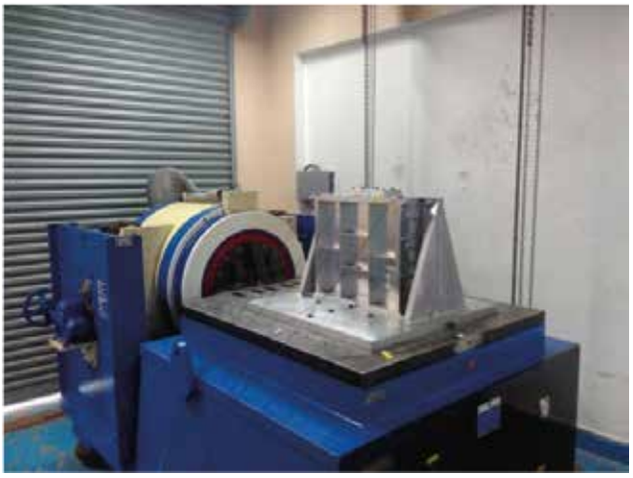


Fig. 9. POLIX detector undergoing vibration test on mechanical shaker

Mechanical fabrication of two more wireframes has been completed and the wiring of these frames is in progress. The main challenge in the wiring process is soldering and epoxying of very thin wires in the range 25-50 microns on a wireframe, which accommodates 354 cathode wires, 30 anti-anode wires and 12 main-anode wires. The workmanship involved in this challenging task has been successfully validated.

On the electronics front, the emphasis this year was to integrate and test the pre-engineering model version of the signal processing electronics. The PCBs for the different subsystems of the signal processing electronics were individually tested and later assembled in a rack system as shown in Fig. 10. The method of charge division and anti-coincidence logic, by using an FPGA based processing electronics, has been fully demonstrated to the required specifications. Currently integrated full system tests are in progress.

Fig. 10. Pre-engineering model of POLIX signal processing electronics

As a part of qualification of the HV unit used in the payload, a thermovac test is planned. The high voltage unit will be placed in a thermovac chamber and temperature cycled, with the electronics for control of high voltage unit placed externally.

The thermovac test setup along with the USB based control and data acquisition system is ready (see Fig. 11). Long term tests to record the normal performance of the system before subjecting the unit to thermovac test is in progress.

Fig. 11. Thermovac test setup for the high voltage unit

For the purpose of collimator calibration and subsequent polarisation tests on POLIX, a 12 m beamline is being designed and constructed. The aim of collimator calibration is to confirm the field of view and flat topped response of the fabricated collimator for on-axis and off-axis sources. The length of the beamline has been chosen to be 12 m to achieve a beam divergence of less than 2 arcmin on a single cell of collimator, which is equivalent to a minimum of 6 points over 0.2 degree of its flat top response. Fig. 12 shows the concept design and the two cabins already installed. Work towards fabrication of components for the beamline is in progress.

Fig. 12. 12m beam line – concept drawing (left) and the actual cabin installed

Interactions with the ISRO team for finalizing the interfaces between the satellite and payload subsystems are in progress. Figure below shows the currently proposed mechanical configuration of the satellite deck, including the electronics

packages of POLIX.

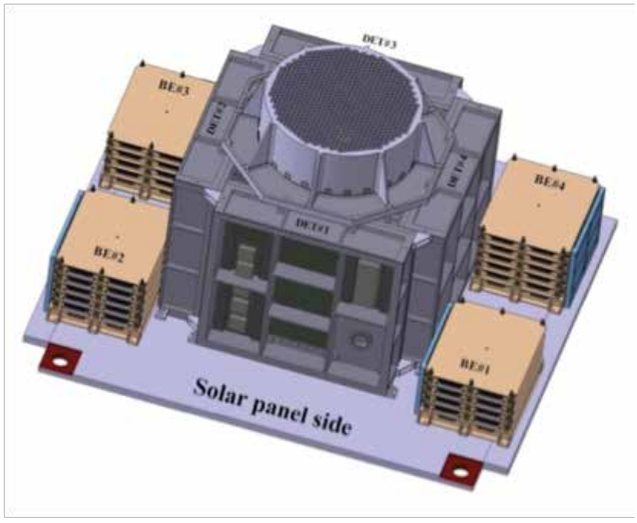


Fig. 13. POLIX mechanical configuration including electronic packages

6. Single-atom Trap experiment

B.S. Girish, Hema Ramachandran (PI)

EEG has been providing technical guidance for the development of a weak-signal detection module for the experiment; the technical work has been in Matlab simulation and hardware and firmware development based on Virtex-6 FPGA platform.

7. Microwave Kappa Measurement

R.Somashekhar (EEG), , Urbasi Sinha(PI), G.Rengaraj, U.Prathwiraj, Surya Narayan Sahoo

EEG has assisted in the experimental setup at Gauribidanur for detecting non-classical paths in microwave based triple slot interference experiments. Guidance was also provided in aspects related to i) experimental setup, ii) measurement, iii) instrument control related programming in labview, iv) data acquisition and v) minimizing noise in the data.

8. STeP

Arasi Sathyamurthy, Mamatha T.S, Ramesh.B (PI)

An Efficient Linear-array Imager (ELI) prototype is being constructed as part of the STeP project. It is a cross-telescope with capacity to form 64 simultaneous beams on the sky using only 16 receivers. EEG has been involved in i) constructing a wired module of the cross telescope, ii) design of front end receiver modules in the frequency range 7-14 GHz and iii) IF processor over 1-2 GHz of the receiver system.

9. Engineering Developments

Investigation of the use of parasitic elements for enhancing the bandwidth of wire dipoles:

A.Raghunathan, Kshitij Sadasivan (VSP student)

A resonant thin wire dipole has inherently narrow bandwidth. However, it can be enhanced by making it thick and profiling its structure appropriately. This has been demonstrated successfully by building a thick and sinusoidally profiled dipole antenna. It has a maximum bandwidth of about 66 %. Investigation is undertaken to further improve the bandwidth by making use of parasitic elements around the dipole antenna. Initial results are encouraging and efforts are on to increase useful operating bandwidth by optimizing the physical parameters of the parasitic elements.

Design and development of cross dipole for monitoring satellite signals in L-Band

A.Raghunathan, Amar, Akhil (VSP students)

The above project was undertaken to monitor satellite signals in L band for carrying out interferometer experiments on a satellite signal. The dipole is designed with integrated balun to convert its balanced to unbalanced output. The dipole is mounted on a circular metal reflector. A prototype was built and tested to validate the functionality of the dipole.

Preliminary studies on the detection of EoR signal using red shifted Helium line

A.Raghunathan, Ramyasri (VSP)

Several experiments across the world are being carried out to detect the EoR signal in redshifted 21 cm line. Sky being very bright at these redshifted frequencies, it is often difficult to model the sky to the required accuracy so that it can be extracted out from the sky data in the process of detecting the EoR signal. Moreover, the radio frequency interference is also severe at these frequencies. So, it is challenging to detect EoR signal under these circumstances. As an alternative, there is a possibility of detecting EoR signal through redshifted Helium line, which is expected to appear around 600 MHz. Since the sky at this frequency is relatively cooler and is about a few Kelvin, it is not expected to dominate the EoR signal as much s for the Hydrogen 21 cm signal. So we have undertaken a preliminary study to find out the possibility of detecting EoR through Helium line by building a low noise and large dynamic range receiver system in this frequency range.

SCM Group Labs

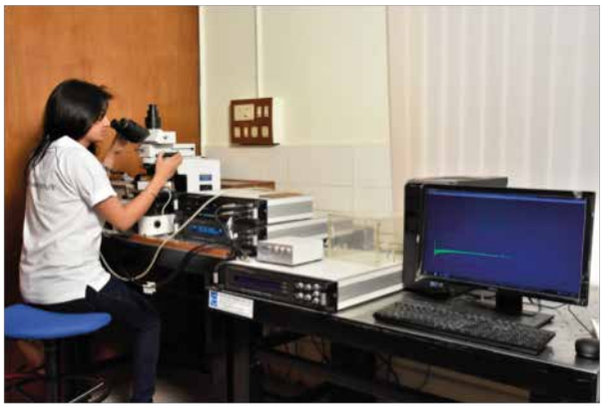
Chemistry Lab

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

Analytical Lab

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

Microscopy and Dielectric Spectroscopy Lab



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

Phase Transition and Electro-Optics Lab

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

Liquid Crystal Display Lab

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

Rheology and Light scattering Lab

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

X-Ray Diffraction Lab

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

Bio-Physics Lab

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

Nanoscale Physics of Soft and Living Matter Lab

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

Electrochemistry and Surface Science Lab

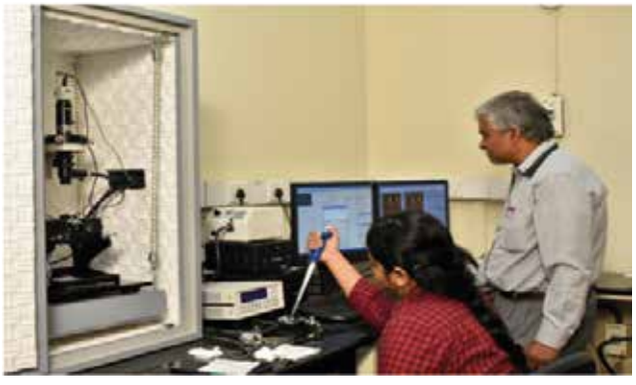
The lab performs controlled experiments on test surfaces in electrochemical cells using electrochemical instruments such as potentiostats, frequency response analyzer and lock-in amplifier. An electrochemical quartz crystal microbalance is used to measure mass changes on the surface in situ. Characterization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

tunnelling microscopy, atomic force microscopy, scanning electron microscopy etc.

Scanning Electron Microscope Lab

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

Atomic Force Microscope Lab



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

Nuclear Magnetic Resonance Lab

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

Micro-Raman Spectroscopy Lab

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

Magnetic studies Lab

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

Photophysical studies Lab

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

Mechanical Engineering Services

The Mechanical Engineering Services (MES) provides 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 for various labs as well as overall infrastructure development of the campus and its facilities. MES mainly consists of a Basement workshop with multiple machines, 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.

With the induction of a new CNC Milling machine from Ace Manufacturing Systems (AMS 850V), MES aims to further develop the quality and precision of machined components. Apart from the controller which is from Siemens(828d) the AMS 850V model is indigenously made in India, it is a 3-axis Vertical Milling Center (VMC) equipped with Automatic Tool Change (ATC) which can accommodate 24 tools and a twin arm changing system. It has a position accuracy of 0.01 mm and a repeatability of +/-0.005 mm. This machine will help in fabrication of intricate components with improved accuracy and in lesser time.

List of major works carried out in MES sections from April 2016 to March 2017

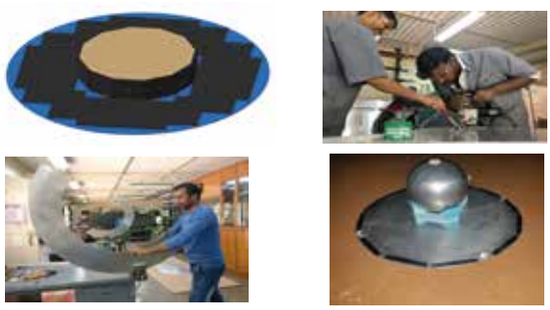
CAD modeling and fabrication

- EOR SARAS Antenna tiles layout
- Fibre force setup for SCM
- Copper cavity setup for SCM
- Bio reactor experimental setup
- Rubidium cell heater experimental setup
- Line Camera setup
- Horn Antenna
- SS vacuum chamber top plate
- Cold Ion Experimental setup

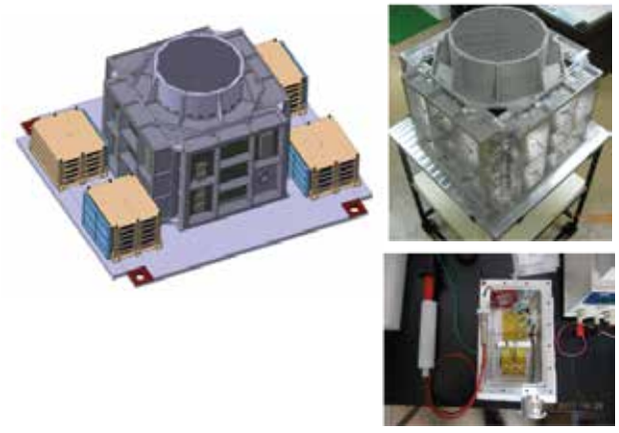
Other works

- Atom cavity experimental setup
- External cavity diode laser assembly for LAMP
- Fabrication of Magneto optical Trap for LAMP
- Bio reactor components fabrication for SCM
- Electronic chassis painting work for BCI lab
- Electronic breadboard paint work
- Student room wooden table fabrication

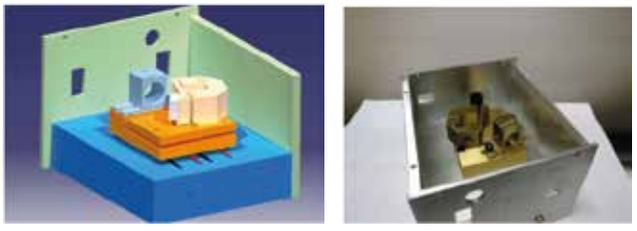
CAD designing and fabrication of EOR (SARAS) Antenna



Design and Fabrication of X-ray polarimeter casing



Thermo vacuum chamber for high voltage DC-DC device-X ray Lab



Design and Fabrication of External
cavity diode laser for quantum interaction laboratory

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 is a hybrid library comprising of both print and electronic information resources. The library is central to all the research and science communication activities of the Institute. Library caters to both general and specialized information needs of its users. Currently, the library has a total collection numbering 69927, comprising of books and bound volumes of journals. Of this, 28800 are books and 41127 are bound volumes of journals. Library subscribed to 51 e-journals, 76 Print journals during the year. Additionally, the library has 1805 non-book materials that include scientific slides, CD-ROMS, DVD's and Audio/video tapes. All the functions of the library are completely automated using LIBSYS – Library automation software.

Library activities

Our continued partnership with National Knowledge Resource Consortium has brought in online access to 4600 journals published by 15 publishers. The Library web page has been continuously upgraded to provide a single window access to all the information resources including consortium online resources. Memoirs of RRI volumes 67 to 70 were compiled. One copy of the memoirs is displayed in the Directors office and another in the Library. Plagiarism check of 3 theses submitted for the award of the doctorate was done at the library. ResearcherID of the entire faculty is regularly updated. Article processing charges (APC) is a new publishing model where the authors are charged by the publishers to make their research work accessible through an open access journal or a hybrid journal. APC at RRI is handled by Library. An MOU with Gubbi Labs, a social media centre, has resulted in 6 news items appearing in popular dailies based on RRI research. RRI library plays a major role in this outreach activity.

Digital Library

e-sangrah - is the official Raman Research Institute Digital Repository (RRIDR). This Institutional repository is built using an open source software DSpace and is currently hosted on version 5.4. Scholarly publications are uploaded regularly. Digitization of archival materials, photographs, and audio/video is continuing from previous years. Theses submitted to RRI are also uploaded to the repository. Number of uploads during the year were 114, and the total records on RRIDR are 7916. The process of updating "Imprints-collection", an off shoot of RRI digital repository, has continued and currently has 32 profiles of superannuated scientists and also of all those scientists who have left RRI to pursue assignments elsewhere and have left behind some imprint in the form of publications with RRI affiliation.

Training activity

RRI library supports manpower development programs by giving internship training to the students of Bangalore University, Kuvempu University and Shri Jayachamarajendra Government Polytechnic for Women. During the year of this report, more than ten students from Library Science departments were trained.

Events Organized

1. J-Gate training program from Informatics was held on 2nd June 2016.
2. Library orientation to fresh graduate students was held on 28th July 2016.
3. Thompson Reuters event on Web of Science was jointly organized by RRI and the Indian Academy of Sciences on 28th September 2016.
4. Demonstration of Grammarly took place on 5th October 2016.
5. The second lecture of the KALA Lecture series was held on 24th March at RRI. The title of the talk was "Professionalism and Ethics," and the speaker was Dr. B.A. Kanchan Garg, Professor, COE & Dean Research (In-charge), PES University, Bengaluru.

Computer Facility

The Computer group handles the various computing needs of different groups and departments at Raman Research Institute and provides support for the computing facilities.
The group also provides and manages services like Email, Web server, Print server and printing, VPN, Digital Repository, Library Management System, LAN, Wireless LAN and internet access, etc.

The implementation of Open Source Library Management Software KOHA which was taken up by the Library was completed with our help. Records from the existing LMS was exported and imported into KOHA. The Library has started using the software for managing the transactions.

The internet link at the Gauribidanur field station was upgraded to use 100 Mbps link of NKN replacing the earlier 2 Mbps link from BSNL; this was done with the help of NIC/NKN. In the field station, a fiber was laid from the IIA Digital Laboratory to the RRI lab to extend the NKN link.

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 (www.rri.res.in).

Currently 89 students from all over India are enrolled in the PhD programme and conducting research with scientific staff members from the four broad research groups at the Institute. Last year 6 PhD theses were completed and submitted for review:

1. Karthik H.S.: Quantum Information theoretic approach to explore non-classical correlations and uncertainty

2. Sourabh Paul: Study of redshifted HI from the Epoch of Reionization era

3. Lijo Thomas George: A study of radio relic and radio halo emission in galaxy clusters

4. Avinash B.S.: Synthesis, characterization and properties of some novel discotic nanocomposites

5. Hegde C.S.: Tagged particle diffusion in one-dimensional stochastic systems

6. Jagdish C. Joshi: Gamma rays, Neutrinos & Antiprotons from Interactions of Cosmic rays

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 post doctoral 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. The reason is that RRI does not wish to have postdoctoral fellow working in isolation. Rather a healthy amount of mutually beneficial interaction with the 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 post doctoral researcher and have a proven track record of being able to conduct original and independent research can apply for a limited number of Pancharatnam Fellowships offered at RRI. Here too, applications are accepted throughout the year and the processing takes about 4 to 6 months. The fellowship is for 3 years. Further details about the Postdoctoral and Pancharatnam Fellowships can be found on the RRI website

Currently, there are 16 postdoctoral and Pancharatnam fellows and one DST INSPIRE Faculty fellow 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, assist in the research, by joining our research staff in one of their professional research works. These opportunities arise when the research staff member has a research activity that requires specialized help that is technical, computational or analysis and cannot be done by the scientific and technical members of the Research Facilities. 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 past year 26 personnel were involved in research activities via the Research Assistant 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 Program 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 past year 90 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 frequently visit various other institutions both abroad and at home to attend conferences and workshops. These events play an important role in providing an opportunity to exchange ideas with the scientific community at large and thus set the stage for future collaborations with researchers from other institutions, both within India and abroad. Last year, scientific staff and students of the Institute attended numerous conferences in India, USA, Australia, Japan, UK, Spain, Italy, Germany, France, Switzerland, Israel, Netherlands, Taiwan, Korea, Ireland, Austria and Canada.

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

During the last year, RRI invited speakers from all over 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

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

Last year there were altogether 99 scholars who visited RRI from both Indian and international institutions. RRI is happy to have so many friends and thanks all of them for contributing to the wonderful diversity and dynamism of the research atmosphere at the Institute.

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

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 & Nayantara Gupta are the organizers of this regular event. The RRI Science Forum is held on Thursdays between 3:30-4:30pm.

Talks at this forum is comprised 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 2016-2017, the forum continued to be a great platform to learn about and appreciate the breadth of research done in RRI.

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

Extramural Activities

Pubic 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 heritage museum containing collections of Professor C V Raman that is located on campus. Apart from these general interactions, over the years many college students have gained hands-on experience working with our sophisticated Radio Telescopes at our Gauribidanur field station. All of these traditions continued in 2016-17 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.

HOLI: Hands on Learning Initiative

Several students at RRI have been part of an outreach effort called HOLI Byte. This is a podcast series from the Hands On Learning Initiative (HOLI). The podcasts are available online: soundcloud.com/holi-hands-on-learning-initiative. Podcasts on topics ranging from the Milky Way to Brownian Motion, Gravitational Waves to Rocket Propulsion Systems have been released in different languages including English, Hindi and Tamil with more languages to come. The following members from RRI contributed to HOLI Byte: Mayuri S Rao (Founding Member of HOLI), Gayathri Raman, Priyanka Singh, Nomaan, Nirmal Iyer, Divya Jayasankar, Raj Prince, Deepak Gupta, Lijo Thomas, Saurabh Singh and Aditi Vijayan.

HANDS-ON Radio Astronomy camp organised and conducted by Avinash Deshpande

Despite the several student internship programs offered by the various Indian research institutes providing useful research experience to typically a few hundred students each year, an overwhelming majority of the 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 is missed to be attracted to graduate studies and research in astronomy. The initiatives such as the "Radio Astronomy Winter School for College students" (RAWSC, since 2008) and the "Pulsar Observing for Students" (POS, since 2012) aimed 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 the 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 our Gauribidanur Field Station and at RAC, Ooty. The focus in these camps is on hands-on experience with instrumentation/ observation/ measurement analysis, thus distinct from the other initiatives that are already in place. In addition to the hands-on component, the 2+week camp will introduce undergraduate and masters students to radio astronomy, basic concepts and advance topics/techniques.

Avinash Deshpande with students at the CHERA camp conducted at RAC, Ooty

May – July 2016 – 12 students from IIT Indore, Kharagpur, IISER Mohali, Thiruvananthapuram, BITS Pilani, and Maulana Azad Urdu University, Hyderabad attended the Indian SWAN (Sky Watch Array Network) HANDS-ON summer 2016 camp at our Gauribidanur field station.

Dec. 2016 – Jan. 2017 - 22 students from IIT Indore, Kharagpur, IISER Mohali, Thiruvananthapuram, BITS Pilani, and Maulana Azad Urdu Iniversity, Hyderabad, IISER Tirupathi, Central University, Hyderabad and University of Hyderabad attended the Indian SWAN (Sky Watch Array Network) HANDS-ON winter 2016 camp at our Gauribidanur field station.

5-22 June 2016 - 12 students from IIT Indore, Kharagpur, IISER Mohali, Thiruvananthapuram, BITS Pilani, and Maulana Azad Urdu Iniversity, Hyderabad, IIT Varanasi, IISER Kolkata, Cotton College State University, Guwahati and Newman College, Thodupuzha attended the Camp for Hands-on Experience in Radio Astronomy (CHERA) at RAC, Ooty

Visits to Gauribidanur Field station organised by Ramesh B. and H.A. Ashwathappa

8 September 2016 - Field visit by 52 diploma girl students from Govt. Polytechnic for Woman, Hindupur.

7 October 2016 - Field visit by 46 Engineering students from BIT Institute of Technology, Hindupur.
23 February 2017 - Field visit by 30 Engineering students from SJCIT, Chikkaballapur.

Visits to RRI by students from various colleges in Bengaluru

26 April 2016 –visit by 40 Electronics Students from Department of Electronics & Communication, B M S College of Engineering, Bengaluru.

18 May 2016 – visit by students from 20 Schools - Educational Initiative - under the "ASSET Summer Programme (ASP)" organised and developed by a faculty from ISI.

29 June 2016 – visit by 7 Students from "The Climber" - An Institute helping students to find their passion and pursue it.

7 November 2016 – A batch of 50 students from Kautilya Vidyalaya, Mysore visited our Institute to commemorate Sri C V Raman's birthday

23 January 2017 - 45 school students from Acharya Bangalore B School, Bengaluru visited our Institute as part of their science curriculum.

28 February 2017 – Around 100 school students visited our Institute as part of the National Science Day celebrations organized jointly by Breakthrough Science Society and RRI.

4 May 2017 - 8 meritorious students from Aryabhat Foundation for Promoting Basic Science, visited our Institute and interacted with our scientist

Andal Narayanan (LAMP) preparing to deliver a talk to students visiting our campus. Manjunatha G. (Public Relations Officer, RRI) helped in organizing the event.

12 July 2017 - A batch of 30 M.Sc. (Physics) students from Sathyabama University, Chennai visited our Institute as part of their science activities.

RRI at the India International Science Festival

Raman Research Institute participated in the 2nd India International Science Festival, IISF 2016 that was held at CSIR-National Physical Laboratory, New Delhi during 7th–11th December 2016. One of the many events at IISF 2016 was a Mega Science & Technology Expo with an audience comprising of a wide range of visitors - high-school students, undergraduates, graduates, PhD students, academics from the scientific fraternity, Ministry officials and also the general public.

Raman Research Institute presented its research highlights at this Mega Science and Technology event. The Institute had a stand-out stall within which were sixteen posters depicting some of our research achievements. Apart from an overview panel where we introduced our Institute, there was also a

poster highlighting and giving examples of recent research outcomes. The remaining fourteen posters discussed (i) Brain-Computer Interface, a low cost technology that enables an individual to control devices using the electrical activity in their brain (ii) Liquid Crystal Displays (iii) MWA (Murchison wide field Array radio telescope), a precursor to Square-Kilometre Array project, (iv) Digital spectrometers for precision radio astronomy, (v) Wide-band antennas for wide bandwidth precision astronomy and remote sensing of terrain, (vi) X-Ray Polarimeter (POLIX), a payload on ISRO's XPoSat mission (vii) Discotic (Disc like) liquid crystals used in LCD screens for wide angle viewing, (viii) Soil under the microscope, some results on soil properties with relevance to landslides and river delta formation (ix) Micro-extension rheometer for understanding the structure – property relations of entities like axons of neuronal cells, spider silk and thin polymeric strands (x) Atom, Ion, Molecule hybrid cavity for studying multi-species interaction at low temperatures, (xi) Testing device for milk adulteration, a technology with societal relevance for detecting synthetic milk, (xii) Coarse quantum

measurement, a method to account for the limitations imposed on an observer by the available resources. (xiii) Novel strategies for DNA sequencing, biosensing for chromatin biophysics and understanding mechanosensing in cancer cells and (xiv) Real-time imaging through fog, a low cost technique that enables instant imaging through turbid media like fog.

The highlighted topics have been chosen such that they provide an overall picture of not only the socially relevant technologies that we have built in-house but also of our basic science advances. Live demonstration sessions were organised with the hand-held milk purity-testing device. It is to be noted here that the basic research behind the milk-purity testing device was completed at the Electrochemistry lab at RRI while the final electronic device was designed and produced by the Department of Electronics Systems and Engineering, Indian Institute of Science and the DST-National Hub for Health care Instrumentation (NHHID) at Anna University, Chennai.

RRI participated at the India International Science festival. Naresh V.S., Debarshini Chakraborti and Sarabagopalan G represented RRI at this festival. The Stall shown in picture was selected as the best stall and Sarabagopalan received the award for the same on behalf of the RRI.

G. Sarabagopalan, Naresh V.S. and Debarshini Chakraborty represented RRI at the exhibition and won the Best stall award for the Institute.

Official Language Activities

Raman Research Institute (RRI) has been taking several initiatives to promote the official language (OL) in our day to day activities.

During the period April 2016 to March 2017, the Institute organised workshops at regular intervals covering topics specific to administration, computing and technical areas, as listed below

Apart from workshops, the Institute observed Hindi Fortnight from 14th September to 26th September 2016 and conducted several competitions. These competitions were linked with learning tools such as Hindi typing, Hindi writing (Dictation), narrating and describing in Hindi. An oral quiz programme was also organized as a part of the event apart from Antakshari. This fortnight programme witnessed exuberant participation.

During the reporting year, the Institute took note of the Annual Programme issued by the Department of Official Language, Ministry of Home Affairs and tried to orient the targets as prescribed therein. In addition, RRI's official language implementation committee consisting of a member from each group and section meets at the end of every quarter to review the progress and ensures effective compliance of OL policy. See Table on next page for list of speakers.

Others

During the period 2016-17, the RRI community has organized several special conferences, meetings and workshops described in detail in the next section titled 'Events'. Other annual events and activities at RRI include in-house meetings, high teas on superannuation of regular staff, celebratory welcome for each new joining batch of PhD students, college visits, and invitation of college students to the campus. Formal and informal dinners, sports tournaments, concerts, and a variety of cultural programmes, both with invited performers and RRI members themselves, are regular features at the RRI campus.

Sl. No.	Date	Topic	Speaker
1	24 June 2016	Noting, drafting and computing in Hindi	Dr S N Mahesh Sr. Translator, CAIR, Bengaluru
2	14 September 2016	Rajbhasha Prem ki Jarurat	Shri Mahadev G Savadatti Rtd. Assistant Director, Dept of OL
3	26 September 2016	Rashtriya Ekta me Hindi ka Mahatva	Prof Neeru Sinha Maharani Lakshmi Ammani College for Women, Bengaluru
4	23 December 2016	Prasashnik evam Takniki kshetro me Hindi anuprayog	Sri Srinivas Rao Sr. Assistant Officer (OL) BEL, Bengaluru
5	17 March 2017	Invisible pollution in environment, its hazards and remedial measures	Dr Durga Dutt Ozha Former Sr. Scientist-G

Events

Visit to RRI Campus by Parliamentary Standing Committee on Science and Technology, Environment and Forests

On 29th August 2016, the Parliamentary Standing Committee on Science and Technology, Environment and Forests made an official visit to the Raman Research Institute campus as part of a study tour. The Committee was chaired by Hon'ble Member of Parliament, Smt. Renuka Chowdhury. Members of the Rajya Sabha Secretariat as well as representatives from DST and DSIR accompanied them.

This was the first Parliamentary Committee on Science and Technology to visit RRI ever! The visit was over an entire afternoon and evening. Arriving after lunch, they were received at the magnificent Main Building of the Institute by the Director, and introduced to coordinators of the research groups over refreshments in the stately teak wood paneled Council room that nevertheless served as an icebreaker.

The first stop for the historic visit was, of course, a glimpse of the history of the Museum by none other than the experienced Sasikumar, who enlivened the group with his humorous anecdotes and enjoyable reasoning for the science behind the exhibits.

Then it was time to get down to Earth and the group was split into two – one heading east to the X-ray lab and the other heading west to Soft Matter labs.

At the X-ray astronomy laboratory, Biswajit Paul and his team members described the science aims behind the developments, and showed systems and modules that are part of payloads being built in the lab. The Committee members were shown the flight model of the X-ray polarimeter, POLIX, which is being built to fly as the payload on an ISRO mission XPoSat and is expected to be the first X-ray polarimeter mission ever to fly in space! Biswajit also described the future activities for which the groundwork is happening now, such as a reliable X-ray pulsar-based deep-space navigation system for planetary missions.

Meanwhile the group going west first arrived at the Rheology and Light Scattering Laboratory where Ranjini Bandyopadhyay and her students showed various experimental techniques that are being used at present to assess the structure, dynamics and stability of colloidal suspensions. Explanations were given on how dynamic light scattering can be used in the laboratory to quantify the structural details and relaxation times of these colloidal samples. There were also live demonstrations of a colloidal particle being tweezed in their recently installed open optical tweezer setup and a real-time experiment in which the visitors got to see a fractal pattern forming at the interface between a Newtonian and a non Newtonian fluid. The team appreciated all the demonstrations, with Ms. Renuka Chowdhury expressing special interest in the lab's work on clay collapse given the relevance of these studies in the understanding of large-scale geophysical phenomena such as landslides and in the formation of river deltas. Visiting the Cell Biophysics Lab, Pramod Pullarkat and his students were on hand to show examples of how ideas from Physics can help in understanding the dynamics and mechanics of neuronal cells-like mechanical responses, growth, molecular motor-based transport and degeneration. A novel optical- fiber based force apparatus, (designed and developed at RRI; patented), and a Laser based Optical Tweezer (also built at RRI), to measure pico- to nano-Newton scale cellular forces were both demonstrated. The committee members were interested in understanding how the lab combines ideas from Physics, experimental techniques and theoretical principles, with Biology in order to better understand neuronal mechanics and dynamics. The Committee members had good and relevant questioning of the lab efforts on the details of the force apparatus and how neuronal dynamics affect normal functioning of the brain and what disruptions happen in diseases like Alzheimer's.

Of course, the Hon'ble Parliamentarians got to go to all labs and the coordinators were kept busy coordinating their movements between labs and shepherding the subgroups across the campus between the different venues.

All converged on time and on schedule to the discussion room in the Academy building – where a formal meeting was arranged of the standing committee. RRI Director and a few of his colleagues made presentations of the research and activities of the Institute, to invite a discussion amongst the members. The group coordinators were on hand to answer questions in their domains of expertise and the Administrative Officer was present too. A presentation by the Director was followed by presentations by Gautam Soni and also Urbasi Sinha – taking the parliamentarians from cosmology to biophysics to quantum information and communications. At the end of the day there were no questions left unanswered and the meeting ended on a happy note for all.

Then it was time for the Parliamentarians to join the Institute over a High Tea. The occasion was certainly special for RRI and so a special effort was made by the Institute to make this memorable: the Library floor was cleared and the vast room was decked out with regal dining arrangements with choice foods befitting the occasion. Smt. Renuka Chowdhury and the Parliamentarians mingled freely with the staff and talked to students. The atmosphere was easy and relaxed.

The visit was perfectly organized in many ways, thanks to the magnificent effort by everyone at RRI and many more from outside our campus. We received Smt. Renuka Chowdhury on Sunday, the Committee spent a long day at the Campus on Monday, the Director and Lakshmi Saripalli had dinner with Smt. Renuka Chowdhury on Tuesday and we saw them off at the airport on Wednesday. Building relationships with the elected representatives, in particular with those in the Parliamentary Standing Committee on Science and Technology, is necessary and important in Modern Times. The visit also gave us a glimpse into the perspectives of the Committee as we experienced the considered and selective appreciation of the Committee members for the sincerity and energy with which we are doing our science in our own way.

Workshop on CMB Spectral Distortions from Cosmic Baryon Evolution

CMB or rather Cosmic Microwave Background is the oldest 'light' or relic radiation leftover in the Universe from the Epoch of Recombination when free electrons and protons in the primordial soup of 'baryonic' matter in the early Universe had recombined to form neutral hydrogen and helium, effectively rendering the Universe transparent. These relic photons could now travel freely through space and the baryon gas, with almost no charged particles to scatter them, appearing today as a microwave background 'glow' all over the sky. As Penzias and Wilson discovered, to their surprise and delight, the dark night sky is actually bright in microwaves and this relic light is our vision of the Early Universe.

With focus in experimental cosmology moving from precision measurements of angular variations in the intensity of the relic radiation across the sky – which was made by COBE, WMAP and now PLANCK missions – to precision measurements of the spectrum of the relic radiation, RRI hosted a workshop during July 11-15 this year to discuss the theory, experimental methods and ongoing efforts and proposed missions that aim to detect these CMB spectral distortions in the coming decades.

About fifty theorists and experimentalists participated in the event, and the discussions included both ground and space based projects. About half the participants were based overseas and half in Indian institutions. PhD students from RRI and IUCAA working in research areas relevant to the topic also attended.

The scientific program was organized by Ravi Subrahmanyan (RRI), Jens Chluba (Univ. of Manchester), Adrian Liu (Univ. of California, Berkeley), Subodh Patil (Geneva) and Tarun Souradeep (IUCAA). This was not an open meeting but one that was by invitation: the organizers made a framework that included all of the topics that required discussion, then looked for appropriate people to present and lead the topics before inviting them and slowly, over months, put together the program.

The local organizing was ably managed by Debarshini Chakraborty, Lakshmi Saripalli, Manjunatha G., Shailaja V. S. and Vidyamani V, all from RRI. All participants were accommodated on campus and in guest rooms at nearby institutions; all participants were together from breakfast to

dinner on all days and the conference dinner was also wonderfully organized on campus in a transformed terrace of the Library building.

A special feature of the workshop was a half- day session in which S Seetha, Head of the Space Physics division of ISRO gave a talk on 'ISRO space physics missions to date – what has been achieved', which was followed by a talk by Mylswami Annadurai, the director of the ISRO Satellite Centre, on 'ISRO space physics missions: Plans and prospects for future space physics missions'. This was followed by a discussion session on what may be done by the Indian community, in collaboration with friends overseas, towards an Indian participation in ground-based and space-based CMB spectral distortion measurements.

True to its description, it was primarily a discussion meeting focusing on interaction between participants and exchange of ideas. The review talks followed by discussion sessions kept the participants totally engaged on Monday and Tuesday. Wednesday was another full day with a difference – kept aside for a "compulsory" excursion in which all participants were bussed away to spend early morning to late evening together exploring UNESCO World Heritage sites, Shravanabelagola and Halebidu, which are fine examples of Jain culture and 12th century Hoysala architecture. Then Thursday and Friday were again full days at the RRI auditorium discussing CMB spectral distortions.
The intensity of the workshop, the novel theme that brought together many workers from different wavelengths and technologies together on a common platform, the excellent hospitality of the local organizing and the rich range of experience will keep the memory of this meeting alive for years to come. All the talks are on the workshop website at www.rri.res.in/CMB_Main.html

Visit by Canada's Minister of Science

The Minister of Innovation, Science and Economic Development of Canada, the honorable Navdeep Singh Bains, visited the Raman Research Institute, Bengaluru on November 9, 2016. His delegation included Jennifer Daubeny, the Canadian Consul General for South India, who coincidentally is also our neighbor, living a stone's throw away from campus in Sadashivanagar.

The delegation led by Minister Bains first met our Director, and a group of select research staff having significant collaborations with Canada and Canadian research institutes at the stately Institute Council Room. Sumati Surya, Andal Narayanan, V.A. Raghunathan, Shiv Sethi, Urbasi Sinha along with our Institute Administrative Officer Mr. C.S.R. Murthy met Minister Bains.

Sumati Surya who has had deep-rooted research ties with the Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada for some years now, spoke about her very recent Emmy Noether Visiting Fellowship awarded by the Perimeter Institute for 2016-17 by way of which she is one of only seven theoretical physicists selected the world over to spend a year at Perimeter pursuing research and collaborating with the Perimeter scientific community.

Andal Narayanan has spent a year at the University of Calgary, Alberta as a part of her sabbatical recently and shared her experiences with the delegates.

V.A. Raghunathan who had also spent his sabbatical in Canada at the Neutron Scattering Facility of the Chalk River Laboratories, a Canadian Nuclear Research facility located in Deep River, Ontario, spoke about the research he had done there. Shiv Sethi brought Minister Bains and the delegates up to speed with the Square Kilometer Array (SKA) mega project, an ambitious global project to build the world's most sensitive radio telescope to date, in which both India and Canada are signatory members. He also spoke at length on RRI's participation in the Murchison Widefield Array (MWA) telescope, which is a precursor to the SKA located in the remote Western Australian outback. Canada has been playing an increasingly significant role in the MWA project and officially became a member of the MWA consortium starting December 2016.

Urbasi Sinha highlighted the research on quantum computation done at her lab in RRI and the MoU RRI shares with the Institute for Quantum Computing (IQC), University of Waterloo.

An opportunity for a group photo in front of our historic main building presented itself once the meeting got over. The tour concluded with Minister Bains and the Canadian delegates visiting the Quantum Information and Computing Lab at the Telescope building accompanied by the Director and Urbasi Sinha.

Visit by the Director of Israel Space Agency

On 6th December 2016 we welcomed the Director of Israel Space Agency - Dr Avi Blasberger – to the Raman Research Institute. He was accompanied by the Israeli Consul General - Ms Yael Hashavit, Mr Ziv Shalvi – Deputy Chief of Mission, Bengaluru and Dr Shai Moses - Consul for Economic Affairs and the Economic and Trade Department. Dr Blasberger

spent some time with our Director talking about ongoing international collaborations as well as active research programs at RRI, that form an integral part of India's space missions. The visitors spent some time at the X-ray astronomy lab where they were given a tour of the facilities, which included the X-ray polarimeter payload being developed for ISRO's XPoSat, a small satellite to study cosmic X-ray sources in polarization. Incidentally, when launched XPoSat will be the world's first space X-ray polarization mission.

This was followed by a visit to the cosmic microwave distortions laboratory where they were introduced to the science and systems being built there that are aimed at detecting signals from the Epochs of formation of the first atoms, stars and galaxies in the universe. This experimental effort at RRI is with excellent theory support from Prof Rennan Barkana and his students at the Tel Aviv University in Israel, and the discussions were on possibilities for collaboration in a space mission for this science goal. The visit ended with a relaxed lunch at the RRI Guest house.

Prof M.G.K. Menon Remembrance Day

RRI paid rich tribute to Prof M.G.K Menon by organizing a remembrance on January 30, 2017. Prof Menon contributed immeasurably to the development of diverse fields of science and technology in India in a career spanning over five decades. Despite his wide-ranging involvements across the country, Prof Menon had a special concern for RRI and was closely involved in guiding the evolution of the Institute for more than forty years. It was Sir C. V. Raman himself who invited Prof Menon to RRI to play a role in its management. Following the Professor's demise Prof Menon took on the key responsibility of Chairperson of the Raman Research Institute Trust, which he carried out to the very end.

The morning session was chaired by Vivek Radhakrishnan. Profs K. Kasturirangan, B. V. Sreekantan, Jyotsna Dhawan and Roddam Narasimha all shared with the gathering, their memories, personal and professional. A collage of Prof Menon's photos was on display, which surely would have led many of the participants down memory lane.

The theme of the afternoon session, chaired by the Director of the institute, was "Future's discussion" wherein research faculty from the various groups on campus gave talks focusing on their vision for future research avenues in their respective areas of expertise.

Thus, this day was especially fulfilling, wherein in the morning we fondly remembered and celebrated the contributions of Prof M.G.K Menon to the growth of the institute while the afternoon was dedicated to future research ideas which will constantly drive the institute to continue at the forefront of basic sciences scenario in India.

Annual In-house meeting

The RRI In-house meeting is a three-day event organized every year by the third year batch of RRI PhD students. The In-house is a platform that brings together the whole academic community in RRI - students, faculty as well as support staff and it gives them an opportunity to present their work through poster and oral presentations and to get acquainted with the ongoing research in the institute, in laboratories or groups apart from their own. This annual tradition is met with great enthusiasm by the whole campus especially because it allows for a healthy exchange of ideas between RRI members, often with expertise in complementary areas. This year's In-house was no exception, as was evident from the level of participation in the meeting. The meeting was held during May 4th-6th in the Main Building Auditorium.

This year, speakers from across the four research groups and facilities like the Library and the Electronics Engineering Group gave oral presentations of twenty minutes each, through the three days of the event. As many as thirty-one speakers took to the podium and presented their work. Oral presentations included topics such as the new ISRO- approved project of the X-ray Astronomy Lab - "POLIX: A Thomson X-ray Polarimeter", a novel way to describe a rotating black

hole using “Wick rotation in tangent space” and “Surprises in light-matter interactions in one- dimensional continuum”. There was also a poster-viewing session on the last two days of the meeting with about twenty-five odd posters being presented. The presenters introduced all posters in a short session on the first day of the meeting.

The last event on the schedule is usually an hour-long open house discussion. For the third straight year, the open house took up 'Five year limit of PhD Program at RRI and No Stipend-No Accommodation Policy' as the topic of discussion. This year’s open house, luckily for the PhD students, led to an actual change of policy. After the In-house 2016, the Institute announced that during their sixth year at RRI, if unfortunately, they were yet to complete their theses, RRI PhD students would be partially supported.

As has been the norm during previous annual In-house meetings, this year too the meeting concluded with a cultural evening followed by dinner at the Library Building Terrace. The Prasad Academy of Music Foundation, Bengaluru gave an hour-long Carnatic, classical and semi-classical music performance. Students, visiting students, postdoctoral fellows and scientific staff as well as their families took to the stage to display their talents in music and dance. T-shirts, sweatshirts, backpacks, coffee mugs and other merchandise designed by the organizing committee and customized by the RRI logo were also distributed to interested buyers after the event. The organizers this year sold merchandise worth close to 1.5lakh rupees! Clearly the demand for RRI monogrammed merchandise is on the rise.

National Science Day

Raman Research Institute along with the Breakthrough Science Society organized National Science Day on February 28th to mark the discovery of Raman effect by our Institute’s founder Sir C. V. Raman. Around 100 school and college students assembled at RRI to participate in the event. The day kicked off with a brief talk on the significance of National Science Day followed by a popular science talk on “Adopting Scientific Method in Life” by Mr G. Satish Kumar (President, Breakthrough Science Society) and a screening of the popular documentary “Quantum Indians”, a compelling story on the life and work of three of India’s greatest scientists – Sir C. V. Raman, Satyendra Nath Bose and Meghnad Saha. The highlight of the event was surely the opportunity for the students to visit the RRI museum and learn about the science and history behind the various exhibits encased therein. Surely, this day will remain in the memories of the students for a long time to come. Since this day holds special significance for us we sincerely hope with the enthusiasm and cooperation of the RRI community, to celebrate the upcoming National Science Day on a much larger scale by organizing an Open Day.

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, Gulmohar, 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. However, do not walk along the well laid out pathways watching these unfold, 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 most 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

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Light and Matter Physics

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Soft Condensed Matter

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Research Interests: The complex molecular systems are renowned for showing the different types of mesophases as well as polymorphic crystalline phases. Raman Spectroscopy technique is used to probe the changes in molecular vibrational energy levels of different modes and their unique signatures in different phases of a highly polar complex molecular system. The other experimental techniques also have been used to probe the molecular system.
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Adit Raj Sharma
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Alkesh Yadav
Research Interests: Biophysics. In particular - Eukaryoyic cells have a organelle called Golgi complex. Golgi complex is a membraneous structure composed of several flattened sacs called cisternae. It is situated near the Endoplasmic Reticulum. The question being addressed is what sets the number of compartments in a golgi complex based on the functions of golgi
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B Srinivasa Murthy, Stores Officer

Estates and Buildings

GB Suresh, Civil Engineer
Muneeswaran
S Anantha Raman
K Bhoopalan
Gunashekar
C Haridas
KN Srinivas
K Palani
M Rajagopal
K G Narasimhalu
M Ramesh
M Gopinath
Hanumantha
Jayamma
C Lakshmamma
T Murali
Narayana
Sidde Gowda
V Venkatesh
Ramanna
Varalakshmi
C Elumalai
A Ramanna
Bylappa – till 31.10.2016
Lingegowda
D Mahalinga
Mailarappa
Marappa
D Muniraja
S Muniraju
Rangalakshmi
D Krishna
T Mahadeva

Security

E Martin Dass
BM Basavarajaiah
UA Earappa
H Gangaiah
Keshavamurthy
Suresha
K Krishnappa
K Pushparaj
OM Ramachandra
G Ramakrishna
M Sannaiah
H Vaderappa

Transport

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

Canteen & Guest House

N Narayanappa (Consultant)
Shivamallu
Mangala Singh
Muniratna
T Naganna
DB Padmavathy
PC Prabhakar
N Puttaswamy
Uma
Sharadamma

Gauribidanur

Gangaram
Papanna
RP Ramji Naik
NR Srinath

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Consultant Paediatrician:
Dr. MR Baliga

Consultant Physician:
Dr. BV Sanjay Rao

Consultant:
Dr. PH Prasad

Publications

Appendix – I

Papers in Journals

1. Elecrochemical determination of ethanol by a palladium modified Graphene
Nanocomposite glassy carbon electrode
Anupam Kumar, Manne*; Gourang Patnaik, Sai*;
Lakshminarayanan V ;
Ramamurthy, Sai Sathish*
Analytical Letters **50**, 350-363, 2017

2. Moving walls and geometric phases
Facchi, Paolo*; Garnero, Ciancarlo* ; Marmo,
Giuseppe* ;
Samuel, Joseph
Annals of Physics **372**, 201, 2016

3. Negative partial density of states in mesoscopic systems
Satpathi, Urbashi ; Deo, Singha P*
Annals of Physics **375**, 491-514, 2016

4. Influence of pulse width on the laser ablation of zinc in nitrogen ambient
Smijesh N; Rao, H Kavya ; Philip, Reji
Applied Physics A - Materials Science and Processing **122**, 460, 2016

5. Study of nonlinear optical absorption properties of Sb2Se3 nanoparticles in the nanosecond and femtosecond excitation regime
Molli, Muralikrishna* ; Pradhan, Prabin* ; Philip, Reji ; +5 Co-authors
Applied Physics A - Materials Science and Processing **122**, 549, 2016

6. All-optical switching in a continuously operated and strongly coupled atom-cavity system
Dutta, Sourav ; Rangwala S A
Applied Physics Letters **110**, 121107, 2017

7. GMOSS: All-sky model of spectral radio brightness based on physical components and associated radiative processes
Sathyanarayana Rao, Mayuri ; Subrahmanyan, Ravi; Udaya Shankar, N ; Chluba, Jens*
Astronomical Journal **153**, 26, 2017

8. A matched filter technique for slow radio transient detection and first demonstration with the Murchison Widefield array
Feng L* ; Vaulin R* ; Deshpande A A ; Prabhu T ; Udaya Shankar N ; Srivani K S; Subrahmanyan, Ravi ; +23 Co-authors
Astronomical Journal **153**, 98, 2017

9. High-energy sources at low radio frequency: the Murchison Widefield Array view of Fermi blazars
Giroletti M* ; Massaro F* ; Deshpande A A ; Udaya Shankar N ; Srivani K S ; Subrahmanyan, Ravi
Astronomy and Astrophysics **588**, A141, 2016

10. The radio spectral energy distribution of infrared-faint radio sources
Herzog A* ; Dwarakanath K S ; Deshpande A A ; Prabhu T ; Udaya Shankar N ; Srivani K S ; Subrahmanyan, Ravi ; +50 Co-authors
Astronomy and Astrophysics **593**, A130, 2016

11. A single zone synchrotron model for flares of PKS1510-089
Basumallick , Partha Pratim ; Gupta, Nayantara
Astroparticle Physics **88**, 1, 2017

12. The Murchison Widefield array 21 cm power spectrum analysis methodology
Jacobs, Daniel C* ; Hazelton B J* ; Udaya Shankar N ; Prabu T ; Sethi S K ; Srivani K S ; Subrahmanyan, Ravi ; +60 Co-authors
Astrophysical Journal **825**, 114, 2016

13. Low frequency observations of linearly polarized structures in the interstellar medium near the south galactic pole
Lenc E* ; Deshpande A A ; Dwarkanath K S ; Paul, Sourabh ; Prabu T ; Udaya Shankar N ; Sethi S K ; Srivani K S ; Subrahmanyan, Ravi ; +50 Co-authors
Astrophysical Journal **830**, 38, 2016

14. AstroSat/LAXPC reveals the high energy variability of GRS 1915+105 in the chi class
Yadav, J S* ; Misra, Ranjeev* ; Paul, Biswajit ; Ishwara-Chandra C H* ; +9 Co-authors
Astrophysical Journal **833**, 27, 2016

15. First Season MWA EoR Power spectrum Results at Redshift 7
Beardsley A P* ; Udaya Shankar N ; Sethi S K ; Srivani K S ; Subrahmanyan, Ravi ; +65 Co-authors
Astrophysical Journal **833**, 102, 2016

16. Delay spectrum with phase-tracking arrays: extracting the HI power spectrum from the epoch of reionization
Paul, Sourabh ; Sethi S K ; Morales, Miguel F* ; Dwarkanath K S ; Udaya Shankar N; Subrahmanyan, Ravi ; Prabhu T ; Srivani K S ; +50 Co-authors
Astrophysical Journal **833**, 213, 2016

17. AstroSat/LAXPC Observation of Cygnus X-1 in the hard state
Misra, Ranjeev* ; Yadav J S* ; Paul, Biswajit ; +10 Co-authors
Astrophysical Journal **835**, 195, 2017

18. Extragalactic peaked-spectrum radio sources at low frequencies
Callingham J R* ; Ekers R D* ; Gaensler B M* ; Dwarakanath K S ; +25 Co-authros
Astrophysical Journal **836**, 174, 2017

19. Low-frequency observations of the Subpulse Drifter PSR J0034-0721 with the Murchison Widefield Array
S. J. McSweeney*; Bhat N D R* ; Tremblay S.E*; Deshpande A A ; Ord S M*
Astrophysical Journal **836**, 224, 2017

20. Spectral energy distribution and radio halo of NGC 253 at low radio frequencies
Kapinska A D* ; Staveley-Smith L* ; Dwarakanath K S ; Paul S ; Sethi S K ; Udaya Shankar, N ; Subrahmanyan, Ravi ; Prabu T ; Srivani K S ; +25 Co-authors
Astrophysical Journal **838**, 68, 2017

21. Ultrafast and short pulse optical nonlinearity in isolated, sparingly sulfonated water soluble graphene
Perumbilavi, Sreekanth ; Sridharan, Kishore* ; Koushik, Dibyashree ; Sankar, Pranitha ; Pillai, Mahadevan V P* ; Philip, Reji
Carbon **111**, 283-290, 2017

22. Nonlinear optical properties of (1-x) CaFe2O4-xBaTiO3 composites
Woldu, Tesfakiros* ; Raneesh B* ; Sreekanth P* ; Rama Reddy, M V* ; Philip, Reji ; Kalarikkal, Nandakumar*
Ceremics International **42**, 11093, 2016

23. Self-Assembly of silver and gold nanoparticles in a metal-free phthalocyanine liquid crystalline matrix: structural, thermal, electrical and nonlinear optical characterization
Gowda, Ashwath Narayana ; Kumar, Manish ; Thomas, Anitta Rose ; Philip, Reji ; Kumar, Sandeep
Chemistry Select **1**, 1361-1370, 2016

24. Propagation in polymer parameterised field theory
Varadarajan, Madhavan
Class and Quantum Gravity **34,** 1, 015012, 2017

25. Boundary and corner terms in the action for general relativity
Jubb, Ian* ; Samuel, Joseph ; Sorkin, Rafael D* ; Surya, Sumati
Classical and Quantum Gravity **34**, 065006, 2017

26. Adsorption kinetics of phosphonic acids and proteins on functionalized Indium tin oxide surfaces using electrochemical impedance spectroscopy
Jagadeesh R V ; Lakshminarayanan V
Electrochimica Acta **197**, 1-9, 2016

27. Fluctuation theorem for entropy production of a partial system in the weak-coupling limit
Gupta, Deepak ; Sabhapandit, Sanjib
Europhysics Letters **115**, 60003, 2016

28. Aggregation and stability of anisotropic charged clay colloids in aqueous medium in the presence of salt
Ali, Samim ; Bandopadhyay, Ranjini
Faraday Discussions **186**, 455-471, 2016

29. An open voice command interface kit
Ansari, Junaid Ahmed* ; Sathyamurthy, Arasi ; Balasubramanyam, Ramesh
IEEE Transactions in Human Machine Systems **46**, 467, 2016

30. Photo-induced characteristics of azobenzene based gold nanoparticles
Yuvaraj A R ; Lutfor, Rahman M* ; Yosof, Mashitah M* ; Kumar, Sandeep
IET Micro & Nano Letters **12**, 201-204, 2017

31. Physics researchers' perception of advantages and disadvantages of open access journals: A study
Nagaraj M N ; Bhandi M K*
International Journal of Library and Information Studies **7**, 132-143, 2017

32. Violation of no-signaling in higher-order quantum measure theories
Joshi, Karhik S ; Srikanth R* ; Sinha, Urbasi
International Journal of Quantum Information **14**, 1650024, 2016

33. High electrocatalytic oxidation of folic acid at carbon paste electrode bulk modified with iron nanoparticle-decorated multiwalled carbon nanotubes and its application in food and pharmaceutical analysis
D'Souza, Ozma J* ; Mascarenhas, Ronald J*; Dhason A ; +4 Co-authors
Ionics **23**, 201, 2017

34. Optical nonlinearity in multiferroic bismuth ferrite
Francis, Nisha P* ; Dhanuskodi S* ; Muneeswaran M* ; Anitta, Rose ; Giridharan N V*
Journal of Alloys and Compounds **688**, 796-802, 2016

35. An organic dye-polymer (phenol red-poly (vinyl alcohol)) composite architecture towards tunable -optical and -saturable absorption characteristics
Sreedhar, Sreeja* ; Lllyaskutty, Navas* ; Sreedhana S* ; Philip, Reji ; Muneera C I*
J*ournal of Applied Physics* **119**, 193106, 2016

36. Existence of polar switching in the nematic and orthogonal smectic phases in novel four-ring bent-core compounds
Turlapati, Srikanth* ; Khan, Raj Kumar* ; Ghosh, Sharmistha* ; Tadapatri, Pramod; Prathibha R ; Rao, Nandiraju V S*
Journal of Applied Physics **120**, 174101, 2016

37. Laser fluence dependence on emission dynamics of ultrafast laser induced copper plasma
Anoop K K* ; Harilal S S* ; Philip, Reji ; Bruzzese R* ; Amoruso S*
Journal of Applied Physics **120**, 185901, 2016

38. Clusters of galaxies and the cosmic web with square kilometre array
Kale, Ruta* ; Dwarakanath K S ; Lal Vir, Dharam* ; Parekh, Viral ; +6 Co-authors
Journal of Astrophysics and Astronomy **37**, 31, 2016

39. From nearby low luminosity AGN to high redshift radio galaxies: Science interests with square kilometre array
Kharb P* ; Nath, Biman B ; +11 Co-authors
Journal of Astrophysics and Astronomy **37**, 34, 2016

40. Neutron star physics in the square kilometre array era: an Indian perspective
Konar, Sushan* ; Mann, Yogesh* ; Paul, Biswajit ; +14 Co-authors
Journal of Astrophysics and Astronomy **37**, 36, 2016

41. Fast transients with the square kilometre array and its pathfinders: an Indian perspective
Gupta, Yashwant* ; Chandra, Poonam* ; Bagchi, Manjari*; Ramanujam, Niruj M* ; Maan, Yogesh* ; Deshpande A A ; Bhattacharyya, Siddhartha*
Journal of Astrophysics and Astronomy **37**, 37, 2016

42. The Ooty wide field array
Subrahmanya, C R ; Manoharan P K* ;Chengalur, Jayaram N*
Journal of Astrophysics and Astronomy **38**, 10, 2017

43. The receiver system for the Ooty wide field array
Subrahmanya C R ; Prasad P ; Girish B S ; Somashekar R
Journal of Astrophysics and Astronomy **38**, 11, 2017

44. Space weather and solar wind studies with OWFA
Manoharan P K* ; Subrahmanya C R ; Chengalur, Jayaram N*
Journal of Astrophysics and Astronomy **38**, 16, 2017

45. Human centromeric CENP-A chromatin is a homotypic, octameric nucleosome at all cell cycle points
Nechemia-Arbely, Yael* ; Soni, Gautam V ; +11 Co-authors
Journal of Cell Biology **216**, 607, 2017

46. Synthesis of new liquid crystals embedded gold nanoparticles for photoswitching properties
Rahman, Md Lutfor* ; Biswas, Tapan Kumar* ; Sarkar, Shaheen M* ; Yusoff, Mashitah Mohd* ; Yuvraj A R ; Kumar, Sandeep
Journal of Colloid and Interface Science **478**, 384-393, 2016

47. The effects of the small-scale DM power on the cosmological neutral hydrogen (HI) distribution at high redshifts
Sarkar, Abir ; Mondal, Rajesh* ; Das, Subinoy* ; Sethi, S K ; Bharadwaj, Somnath*; Marsh, David J E*
Journal of Cosmology and Astroparticle Physics **04**, 012, 2016

48. Amperometric sensor based on multi-walled carbon nanotube and poly (Bromocresol purple) modified carbon paste electrode for the sensitive determination of L-tyrosine in food and biological samples
Shrestha, Siddharth* ; Mascarenhas, Ronald J* ; D'Souza, Ozma J* ; Satpati, Ashis K* ; Mekhalif, Zineb* ; Dhason A ; Martis, Praveen*
Journal of Electroanalytical Chemistry **778**, 32-40, 2016

49. Squeezing of the mechanical motion and beating 3 dB limit using dispersive optomechanical interactions
Sainadh, Satya U* ; Kumar, Anil M
Journal of Modern Optics **64**, 1121, 2017

50. Observing the emergence of phase biaxiality in a polar smectic A system via polarised Raman spectroscopy
Zhang A* ; Kaur S* ; Kundu, Brindaban* ; Sadashiva B K ; Gleeson H F*
Journal of Materials Chemistry C **5**, 1195, 2017

51. Rapid and facile synthesis of graphene oxide quantum dots with good linear and nonlinear optical properties
Sakho, El hadji Mamour* ; Oluwafemi, Oluwatobi S* ; Perumbilavil, Sreekanth; Philip, Reji ; Kala M S* ; Thomas, Sabu* ; Kalarikkal, Nandakumar*
Journal of Materials Science: Materials in Electronics **27**, 10926-933, 2016

52. Synthesis and comparative studies of phase transition behaviour of new dimeric liquid crystals consisting of dimethyluracil and biphenyl cores
AbdulKarim-Talaqa, Mohammad* ; Srinivasa H T ; Sie-Tiong, Ha* ; Hariprasad S* ; Guan-Yeow, Yeap*
Journal of Molecular Liquids **219**, 765-772, 2016

53. Synthesis and mesomorphic properties of novel Schiff base liquid crystalline EDOT derivatives
Gowda, Ashwath Narayana ; Roy, Arun ; Kumar, Sandeep
Journal of Molecular Liquids **225**, 840, 2017

54. New coumarin carboxylates having trifluoromethyl, diethylamino and morpholino terminal groups: Synthesis and mesomorphic characterizations
Srinivasa H T ; Harishkumar H N* ; Palashamurthy, B S*
Journal of Molecular Structure **1131**, 97-102, 2017

55. Synthesis mesomorphic and theoretical studies of some new unsymmetrical dimeric ethers of 6-amino-1,3 -dimethyluracil and biphenyl cores
AbdulKarim-Talaq, Mohammad* ; Srinivasa H T ; Mohammad, Hameed Madlool* ; Hariprasad S* ; Yeap, Guan-Yeow*
Journal of Molecular Structure **1117**, 201-207, 2016

56. Microfabrication of Fresnel zone plates by laser induced solid ablation
Rodrigues, Vanessa R M* ; Thomas, John* ; Santhosh, Chidangil* ; Ramachandran, Hema ; Mathur, Deepak J*
Journal of Optics **18**, 075403, 2016

57. Manipulation of entanglement sudden death in an all-optical setup
Singh, Ashutosh ; Pradyumna, Siva* ; Rau, A R P* ; Sinha, Urbasi
Journal of the Optical Society of America B **34**, 681, 2017

58. Incorporation of liquid crystalline triphenylene derivative in bulk heterojunction solar cell with molybdenum oxide as buffer layer for improved efficiency
Bajpai, Manisha* ; Yadav ; Neelam *; Kumar, Sandeep ; Srivastava, Ritu*; Dhar, Ravindra*
Liquid Crystals **43(7)**, 928-936, 2016

59. Effect of dispersion of CdSe quantum dots on phase transition, electrical and electro-optical properties of 4PP4OB
Singh U B* ; Pandey M B* ; Dhar R* ; Verma R* ; Kumar, Sandeep
Liquid Crystals **43**, 1075, 2016

60. New mesogenic compounds possessing a biphenyl ester and ether moiety comprising 1,3-dimethylbarbituric acid: synthesis, characterisation and mesomorphic studies
Abdulkarim-Talaq, Mohammad* ; Srinivasa H T ; Suresh, Hariprasad* ; Yeap, Guan-Yeow*
Liquid Crystals **43**, 1174, 2016

61. Ethylenedioxythiophene as a novel central unit for bent-core liquid crystals
Gowda, Ashwath Narayana ; Kumar, Sandeep
Liquid Crystals **43**, 1721-31, 2016

62. Novel oxazepinedione-derived symmetric dimers: synthesis and mesophase characterisation of seven-membered heterocyclic compounds
Abdulkarim-Talaq, Mohammad* ; Srinivasa H T ; Hariprasad S* ; Yeap, Guan-Yeow*
Liquid Crystals **43**, 1739-1747, 2016

63. Bulk heterojunction solar cells made from carbazole copolymer and fullerene derivative with an inserted layer of discotic material with improved efficiency
Bajpai M *; Yadav N* ; Kumar, Sandeep ; Srivastava R*; Dhar R*
Liquid Crystals **44**, 379-386, 2017

64. Parametrizing epoch of reionization foregrounds: a deep survey of low-frequency point-source spectra with the Murchison Widefield Array
Offringa A R* ; Trott C M* ; Sethi S K ; Udaya Shankar N ; Subrahmanyan, Ravi ; Paul, Biswajit ; +30 Co-authors
Monthly Notices of the Royal Astronomical Society **458**, 1057, 2016

65. SALT observation of X-ray pulse reprocessing in 4U 1626-67
Raman, Gayathri ; Paul, Biswajit ; Bhattacharya, Dipankar*; Mohan, Vijay*
Monthly Notices of the Royal Astronomical Society **458**, 1302, 2016

66. Limits on fast radio bursts and other transient sources at 182 mhz using the Murchison Widefield array
Rowlinson A* ; Bell M E* ; Deshpande A A ; Udaya Shankar N ; Srivani K S ; Subrahmanyan Ravi ; Prabu T ; +30 Co-authors
Monthly Notices of the Royal Astronomical Society **458**, 3506-3522, 2016

67. Stellar dynamics around a massive black hole I. secular collisionless theory
Sridhar S ; Touma, Jihad R *
Monthly Notices of the Royal Astronomical Society **458**, 4129-42, 2016

68. Stellar dynamics around a massive black hole II: resonant relaxation
Sridhar S ; Touma, Jihad R*
Monthly Notices of the Royal Astronomical Society **458**, 4143-61, 2016

69. Suppression of galactic outflows by cosmological infall and circumgalactic medium
Singh, Priyanka ; Rana, Sandeep* ; Bagla, Jasjeet S* ; Nath,Biman B
Monthly Notices of the Royal Astronomical Society **459**, 2-8, 2016

70. How unusual is the cool-core radio halo cluster CL1821+643?
Kale, Rute* ; Parekh, Viral
Monthly Notices of the Royal Astronomical Society **459**, 2940-47, 2016

71. The 154 MHz radio sky observed by the Murchiso Wide Field Array: noise, confusion, and first source count analyses
Franzen T M O* ; Jackson C A* ; Deshpande A A ; Prabu T ; Udaya Shankar N ; Srivani K S ; Subrahmanyan, Ravi ; +25 Co-auhtors
Monthly Notices of the Royal Astronomical Society **459**, 3314, 2016

72. A modified WKB formulation for linear eigenmodes of acollisionless self-gravitating disc in the epicyclic approximation
Gulati, Mamta ; Saini, Tarun Deep*
Monthly Notices of the Royal Astronomical Society **460**, 1019, 2016

73. First limits on the 21 cm power spectrum during the epoch of X-ray heating
Ewall-Wice A*; Dillon, Joshua S*; Offringa A R*; Saurabh, Paul ; Prabu T ; Udaya Shankar N ; Sethi S K ; Srivani K S ; Subrahmanyan, Ravi ; +55 Co-authors
Monthly Notices of the Royal Astronomical Society **460**, 4320, 2016

74. Orbital evolution and search for eccentricity and apsidal motion in the eclipsing HMXB 4U 1700-37
Islam, Nazma ; Paul, Biswajit
Monthly Notices of the Royal Astronomical Society **461**, 816-824, 2016

75. Time-domain and spectral properties of pulsars at 154 MHz
Bell M E* ; Murphy, Tara* ; Deshpande A A ; Prabu T ; Udaya Shankar N ; Srivani K S ; Subrahmanyan ; Ravi, +35 Co-authors
Monthly Notices of the Royal Astronomical Society **461**, 908, 2016

76. A high reliability survey of discrete Epoch of Reionization foreground sources in the MWA EoR0 field
Carroll P A* ; Line J* ; Udaya Shankar N ; Sethi S K ; Srivani K S ; Subrahmanyan, Ravi ; +50 Co-authors
Monthly Notices of the Royal Astronomical Society **461**, 4151-4175, 2016

77. Low radio frequency observations and spectral modelling of the remnant of Supernova 1987A
Callingham J R* ; Gaensler B M* ; Dwarakanath K S ; +18 Co-authors
Monthly Notices of the Royal Astronomical Society **462**, 290, 2016

78. How radiation affects superbubbles: Through momentum injection in early phase and photo-heating
Gupta, Siddhartha ; Nath, Biman B ; Sharma, Prateek* ; Shchekinov, Yuri*
Monthly Notices of the Royal Astronomical Society **462**, 4532-4548, 2016

79. Variability study of the high mass X-ray binary IGR J18027–2016 with Swift–XRT
Aftab, Nafisa ; Islam, Nazma ; Paul, Biswajit
Monthly Notices of the Royal Astronomical Society **463**, 2032-2038, 2016

80. Molecular outflows in starburst nuclei
Roy, Arpita ; Nath, Biman B ; Sharma, Prateek* ; Shchekinov, Yuri*
Monthly Notices of the Royal Astronomical Society **463**, 2296-2309, 2016

81. GaLactic and Extragalactic All-sky Murchison Widefield

Array (GLEAM) survey - I. A low-frequency extragalactic catalogue
Hurley-Walker N* ; Dwarakanath K S ; Deshpande A A ; Prabu T ; Udaya Shankar, N ; Srivani K S ; Subrahmanyan, Ravi ; +40 Co-authors
Monthly Notices of the Royal Astronomical Society **464**, 1146-67, 2017

82. A study of diffuse radio sources and X-ray emission in six massive clusters
Parekh, Viral; Dwarakanath K S; Kale, Ruta *, Intema, H*
Monthly Notices of the Royal Astronomical Society **464**, 2752, 2017

83. How multiple supernovae overlap to form superbubbles
Yadav, Naveen* ; Mukherjee, Dipanjan* ; Sharma, Prateek* ; Nath, Biman B
Monthly Notices of the Royal Astronomical Society **465**, 1720-40, 2017

84. Stellar dynamics around a massive black hole III: resonant relaxation of axisymmetric discs
Sridhar S ; Touma J*
Monthly Notices of the Royal Astronomical Society **465**, 1856-78, 2017

85. Galactic synchrotron emissivity measurements between $250° < l < 355°$ from the GLEAM survey with the MWA
Su, H* ; Hurley-walker, N* ; Dwarakanath K S ; +23 Co-authors
Monthly Notices of the Royal Astronomical Society **465**, 3163, 2017

86. Constraining the X-ray AGN halo occupation distribution: implications for eROSITA
Singh, Priyanka ; Refregier, Alexandre* ; Majumdar, Subhabrata* ; Nath, Biman B
Monthly Notices of the Royal Astronomical Society **466**, 3961-72, 2017

87. Photodisintegrated gamma rays and neutrinos from heavy nuclei in the gamma-ray burst jet of GRB 130427A
Joshi, Jagdish C; Razzaque, Soebur*; Moharana, Reetanjali*
Monthly Notices of the Royal Astronomical Society Letters **458**, L79-L83, 2016

88. Little evidence for entropy and energy excess beyond r500 - an end to ICM preheating?
Iqbal, Asif* ; Majumdar, Subhabrata* ; Nath, Biman B ; Ettori, Stefano*; Eckert, Domonique*; Malik, Manzoor A*
Monthly Notices of the Royal Astronomical Society Letters **465**, L99-L103, 2017

89. Temperature measurement during thermonuclear X-ray bursts with BeppoSAX
Beri, Aru* ; Paul, Biswajit ; Orlandini, Mauro* ; Maitra, Chandreyee*
New Astronomy **45**, 48-53, 2016

90. Effects of variability of X-ray binaries on the X-ray luminosity functions of Milky way
Islam, Nazma ; Paul, Biswajit
New Astronomy **47**, 81-87, 2016

91. X-ray and optical orbital modulation of EXO 0748-676: A co-variability study using XMM-Newton
Raman, Gayathri ; Paul, Biswajit
New Astronomy **54**, 122-139, 2017

92. Composition dependent structural, Raman and nonlinear optical properties of PVA capped Zn1-x-yCdxCuyS quantum dots
Vineeshkumar T V* ; Raj, Rithesh D* ; Sankar, Pranitha ; Unnikrishnan N V* ; Pillai, Mahadevan V P*; Sudarsanakumar C*
Optical Materials **58**, 128-135, 2016

93. Improved nonlinear optical and optical limiting properties in non-covalent functionalized reduced graphene oxide/silver nanoparticle (NF-RGO/Ag-NPs) hybrid
Sakho, El hadji Mamour*; Oluwafemi, Oluwatobi S*; Perumbilavil, Sreekanth ; Philip, Reji ; Toomas, Sabu* ; Kalarikkal, Nandakumar*
Optical Materials **58**, 476-483, 2016

94. Tunable emission and excited state absorption induced optical limiting in Tb2(MoO4)3: Sm3+/Eu3+ nanophosphors
Mani, Kamal P* ; Sreekanth, P ; Vimal G* ; Biju P R* ; Philip, Reji ; +3 Co-authors
Optical Materials **62**, 110-118, 2016

95. Role of Mn2+ concentration in the linear and nonlinear optical properties of Ni1-xMnxSe nanoparticle
Anugop B* ; Prasanth S* ; Raj, Rithesh D* ; Sankar, Pranitha ; +3 Co-authors
Optical Materials **62**, 297-305, 2016

96. Ultrafast optical nonlinearity and photoacoustic studies on chitosan-boron nitride nanotube composite films
Kuthirummal, Narayanan*; Philip, Reji ; Mohan, Athira*; Jenks, Cassidy*; Levi-Polyachenko, Nicole*
Optics Communications **371**, 47-50, 2016

97. Theoretical optimal modulation frequencies for

scattering parameter estimation and ballistic photon filtering in diffusing media
Panigrahi, Swapnesh*; Fade, Julien* ; Ramachandran, Hema; Alouini, Mehdi*
Optics Express **24**, 16066, 2016

98. Charge transport in a liquid crystalline triphenylene polymer monolayer at air-solid interface
Gayathri H N* ; Kumar, Bharat* ; Suresh K A* ; Bisoyi, Hari Krishna*; Kumar, Sandeep
P*hysical Chemistry Chemical Physics* **18,** 12101, 2016

99. Photodissociation of trapped Rb2+: Implications for simultaneous trapping of atoms and molecular ions
Jyothi S ; Ray, Tridib ; Dutta, Sourav ; Allouche A R*; Vexiau, Romain* ; Dulieu, Olivier*; Rangwala S A
Physical Review Letters **117**, 213002, 2016

100. Nondestructive detection of ions using atom-cavity collective strong coupling
Dutta, Sourav ; Rangwala S A
Physical Review A **94**, 053841, 2016

101. Two-photon photoassociation spectroscopy of an ultracold heteronuclear molecule
Dutta, Sourav ; Pérez-Ríos, Jesús*; Elliott D S*; Chen, Yong P*
Physical Review A **95**, 013405, 2017

102. Effect of long-range hopping and interactions on entanglement dynamics and many- body localization
Singh, Rajeev* ; Moessner, Roderich* ; Roy, Dibyendu
Physical Review B **95**, 094205, 2017

103. High-energy neutrinos from the gravitational wave event GW150914 possibly associated with a short gamma-ray burst
Moharana, Reetanjali* ; Razzaque, Soebur* ; Gupta, Nayantara ; Meszaros, Peter*
Physical Review D **93**, 123011, 2016

104. Exact distributions of cover times for N independent random walkers in one dimension
Majumdar,SatyaN*;Sabhapandit,Sanjib;Schehr,Gregory*
Physical Review E **94**, 062131, 2016

105. Velocity distribution of driven inelastic one-component Maxwell gas
Prasad V V *; Das, Dibyendu *; Sabhapandit, Sanjib ; Rajesh R*
Physical Review E **95**, 032909, 2017

106. Stability of the sectored morphology of polymer crystallites
Alageshan, Jaya Kumar ; Hatwalne, Yashodhan ; Muthukumar M
Physical Review E **94**, 032506, 2016

107. Driven inelastic Maxwell gas in one dimension
Prasad V V* ; Sabhapandit, Sanjib ; Dhar, Abhishek* ; Narayan, Onuttom*
Physical Review E **95**, 022115, 2017

108. Elasticity of smectic liquid crystals with in-plane orientational order and dispiration asymmetry
Alageshan, Jaya Kumar;
Chakrabarti, Buddhapriya*;Hatwalne, Yashodhan
Physical Review E **95**, 022701, 2017

109. Collisional cooling of light ions by cotrapped heavy atoms
Dutta, Sourav ; Sawant, Rahul ; Rangwala S A
Physical Review Letters **118**, 113401, 2017

110. Ring closure in actin polymers
Sinha, Supurna ; Chattopadhyay, Sebanti*
Physics Letters A **381**, 1029-32, 2017

111. Ultrafast laser produced zinc plasma: Stark broadening of emission lines in nitrogen ambient
Rao, Kavya H* ; Smijesh N* ; Nivas, Jijil JJ* ; Philip, Reji
Physics of Plasmas **23**, 043503, 2016

112. Spatio-temporal optimization of a laser produced Al-plasma: Generation of highly ionized species
Smijesh N* ; Rao, H Kavya* ; Klemke N* ; Philip, Reji ; Litvinyuk V* ; Sang R T*
Physics of Plasmas **23**, 113104, 2016

113. Optical and nonlinear optical limiting properties of AgNi alloy nanostructures
Udayabhaskar R* ; Sreekanth P ; Karthikeyan B*
Plasmonics **11**, 1461-1466, 2016

114. Liquid crystals in photovoltaics: a new generation of organic photovoltaics
Kumar, Manish ; Kumar, Sandeep
Polymer Journal **49**, 85-111, 2017

115. Fabrication of low noise Borosilicate glass nanopores for single molecule sensing
Bafna, Jayesha A ; Soni, V Gautam
Public Library of Science One, 0157399, 2016

116. Ionospheric modelling using GPS to calibrate the

MWA. II: Regional ionospheric modelling using GPS and GLONASS to estimate ionospheric gradients
Arora B S* ; Morgan J* ; Ord S M* ; Dwarakanath K S ; +15 Co-authors
Publications of the Astronomical Society of Australia (PASA) **33**, e31, 2016

117. Bent-shaped molecules with terminal trimethylsilyl group: synthesis and characterization
Srinivasa HT; Hariprasad S
Research Journal of Chemical Science **6**(**12**), 25-31, 2016

118. Oscillatory extensional rheology of microscale fluid filaments
Paul, Sagnik* ; Kalelkar, Chirag *; Pullarkat, Pramod A
Rheologica Acta **56**, 113-122, 2017

119. Synchronization of conformational chirality in mixtures of achiral bent-core molecules
Anjali S ; Pratibha R
RSC Advances **6**, 53830, 2016

120. Size-strain distribution analysis of SnO2 nanoparticles and their multifunctional applications as fiber optic gas sensors, supercapacitors and optical limiters
Manikandan K* ; Dhanuskodi S* ; Anitta, Rose ; Maheswari N* ; Muralidharan G* ; Sastikumar D*
RSC Advances **6**, 90559-70, 2016

121. Nonlinear transmittance and optical power limiting in magnesium ferrite nanoparticles: effects of laser pulsewidth and particle size
Perumbilavi, Sreekanth; Sridharan, Kishor* ; Abraham, Ann Rose* ; Janardhanan, Harsha P* ; Kalarikkal, Nandakumar* ; Philip, Reji
RSC Advances **6**, 106754, 2016

122. Use and awareness of open access resources among researchers: a case study of Raman Research Institute
Nagaraj M N ; Bhandi M K*
SRELS Journal of Information Management **53**, 381-386, 2016

123. Real-time imaging through strongly scattering media: seeing through turbid media, instantly
Sudarsanam, Sriram ; Mathew, James ; Panigrahi, Swapnesh*; Fade, Julien*; Alouini, Mehdi*; Ramachandran, Hema
Scientific Reports **6**, 25033, 2016

124. Observation of the Chiral and Achiral hexatic phases of self-assembled Micellar polymers
Pal, Antara ; Kamal, Md. Arif ; Raghunathan V A
Scientific Reports **6**, 32313, 2016

125. Pseudo-polar tilted smectic phases exhibited by bent-core hockey stick shaped molecules
Malkar, Deepshika ; Sadashiva B K ; Roy, Arun
Soft Matter **12**, 4960, 2016

126. Active fluidization in dense glassy systems
Mandal, Rituparno* ; Bhuyan, Pranad Jyoti*; Rao, Madan; Dasgupta, Chandan*
Soft Matter **12**, 6268, 2016

127. Cellular structures arising from viscoelastic phase separation in binary mixtures of thermotropic liquid crystals
Anjali S ; Pratibha R
Soft Matter **13**, 2330, 2017

128. Effect of high concentration of colloidal gold nanoparticles on the thermodynamic, optical, and electrical properties of 2, 3, 6, 7, 10exabutyloxytryphenylene discotic liquid crystalline material
Mishra, Mukesh* ; Kumar, Sandeep ; Dhar, Ravindra*
Soft Matter **15**, 34-44, 2017

129. Enhanced liquid crystal properties in symmetric ethers containing the oxazepine core: synthesis and characterization of seven member heterocyclic dimers
Abdulkarim-Talaq, Mohammad*; Srinivasa H T ; Hariprasad S* ; Yeap, Guan-Yeow*
Tetrahedron **72**, 3948, 2016

130. Gold nanoparticles in plastic columnar discotic liquid crystalline material
Mishra, Mukesh* ; Kumar, Sandeep ; Dhar, Ravindra*
Thermochimica Acta **631**, 59-70, 2016

Papers in Conference Proceedings

1. Evolution of scholarly publishing and library services in astronomy - impact, challenges, and opportunities
Wesley, Hema* ; Sheshadri, Geetha
Proceedings of the XXIX (29th) International Astronomical Union General Assembly, 2015, Volume 11, Issue 29A, Page 156-164 2016

2. X-Shaped Radio Galaxies and the Nanohertz

gravitational wave background
Roberts, David H*; Saripalli, Lakshmi; Subrahmanyan, Ravi
Proceedings of the XXIX(29th) International Astronomical Union General Assembly, 2015, Volume 11, 29B, page 319, 2016

3. Large Area X-ray proportional counter (LAXPC) instrument onboard ASTROSAT
Yadav, J S* ; Agrawal P C* ; Paul, Biswajit ; +9 Co-authors
SPIE Proceedings Vol. 9905, Space Telescopes and Instrumentation Ultraviolet to Gamma Ray, Page 1D, 2016

4. The LOFT mission concept: a status update
Feroci M* ; Bozzo E* ; Paul, Biswajit ; +250 Co-authors
SPIE Proceedings 9905, Space Telescopes and Instrumentation Ultraviolet to Gamma Ray. page - 1R, 2016
5. XIPE: the X-ray imaging polarimetry explorer
Soffitta P* ; Paul, Biswajit ; +250 Co-authors
SPIE Proceedings Vol. 9905, Space Telescopes and Instrumentation Ultraviolet to Gamma Ray, Page 15, 2016

6. Supramolecular Nanocomposites: Dispersion of Zero-, One- and Two dimensional Nanoparticles in discotic liquid crystals
Sandeep Kumar
Journal of Physics: Conference Series 704, 012022, 2016

7. Wideband antennas for precision spectral radiometers for cosmology
Subrahmanyan, Ravi; Raghunathan, Agaram; Udaya Shankar N; Singh, Saurabh; Puthige, Sharath; Nivedita
ICEAA-IEEE APWC 2016, International Conference on Electromagnetics in Advanced Applications (ICEEA 2016), Held at Cairns, Australia from 19-23, September, 2016

8. Women in Academics: From Mythology to Modern age
Meera B M
National Conference on "Women in Academic Institutions: Opportunities, challenges and constraints, organized by Women Empowerment Cell, Sindhi College of Commerce, Bangalore, 9th February 2017, P. 2-6

Books Published

1. Liquid crystal dimers
Pal S K ; Kumar, Sandeep
Cambridge University Press, 2017

Book Chapters

1. Nanoparticles in Discotic Liquid Crystals
Kumar, Sandeep
In: "Liquid crystals with nano and microparticles", Vol 2, World Scientific Publishing, 461-496, 2017

2. Quantum dynamics
Ladda, Alok; Varadarajan, Madhavan
In: "Loop quantum gravity: The first 30 years", Edited by Abhay Ashtekar and Jorge Pulin,
World Scientific Publishing, P.69, 2017

Popular Articles

1. AstroSat/LAXPC observed 4U 1630-472 on very first day of a new outburst
J. S. Yadav, Jai Verdhan Chauhan, P. C. Agrawal, H. M. Antia, Mayukh Pahari, V. R. Chitnis, Ranjeev Misra, Dhiraj Dedhia, Tilak Katoch, P. Madhwani, R. K. Manchanda, B. Paul, Parag Shah, Diego Altamirano, P. Gandhi, K. H. Navalgund, K. S. Sarma, S. Seetha, K. Subbarao, ATEL 9515
Astronomers Telegram, 2016

2. Murchison Widefield Array upper limits on radio emission from the Proxima Centauri exoplanetary system at 154 MHz.
Bell M E* ; Lynch C* ; Dwarakanath K S ; +35 co-authors
Astronomer's Telegram 9465, 2016
3. Mind the gap: reflections on the art of science
Subrahmanyan, Ravi
Current Science **112**, 699, 2017

4. Gas between the stars: what determines its temperature?
Nath, Biman B
Resonance, November 2016

In Press

In Journals

1. Scalar field green functions on causal sets
Ahmed, Nomaan S ; Dowker, Fay* ; Surya,Sumati
Classical & Quantum Gravity **34**, 124002, 2017

2. Effects of aging on the yielding behaviour of acid and salt induced Laponite gels
Ranganathan, Venketesh Thrithamara ; Bandopadhyay, Ranjini
Colloids and Surfaces A: Physicochemical and Engineering Aspects **522**, 304, 2017

3. The effects of the small-scale behavior of dark matter power spectrum on CMB spectral distortion
Sarkar, Abir; Sethi, Shiv K; Das, Subinoy
Journal of Cosmology and Astroparticle Physics 07(2017)012

4. Time-resolved fluorescence and absence of Förster resonance energy transfer in ferroelectric liquid crystal-quantum dots composites
Singh D P *; Pandey S* ; Manohar R* ; Kumar, Sandeep ; Pujar G H ; Inamdar S R
Journal of Luminescence **190**, 161-170, 2017

5. Novel achiral four-ring bent-shaped nematic liquid crystals with trifluoromethyl and methyl substituents in the central molecular core: an unusually large Kerr constant in blue phase III of nematic-chiral dopant mixture
Khan RK*; Turlapati S*; Rao NVS*; Pratibha R; Drzewinski W*; Dabrowski R*; Ghosh S*
Journal of Materials Chemistry C 5, 6729, 2017

6. Soft discotic matrix with 0-D silver nanoparticles: impact on molecular ordering and conductivity
Shalaka Varshney; Manish Kumar; Ashwathanarayana Gowda; Sandeep Kumar
Journal Molecular Liquid 238, 290–295, 2017

7. Silver nanodisks in soft discotic forest: Impact on self-assembly, conductivity and molecular packing
Manish Kumar; Shalaka Varshney: Ashwathanarayana Gowda; Sandeep Kumar
Journal Molecular Liquid **241**, 666–674, 2017

8. Thermodynamic study of a plastic columnar discotic material 2, 3, 6, 7, 10, 11 hexabutyloxytriphenylene dispersed with gold nanoparticles under elevated pressure
Tripathi, Pratibha* ; Mishra, Mukesh* ; Kumar, Sandeep ; Dhar, Ravindra*
Journal of Thermal Analysis and Calorimetry **129**, 315-322, 2017

9. Discotic liquid crystals derived from polycyclic aromatic cores: From smallest benzene to utmost graphene
Gowda, Ashwathanarayana ; Kumar, Manish ; Kumar, Sandeep
Liquid Crystals 2017

10. New symmetric azobenzene molecules of varied central cores: Synthesis and characterisation for liquid crystalline properties
Srinivasa HT
Liquid Crystals **44**, 1384-1393, 2017

11. Synthesis and characterisation of some new chalcone liquid crystals
HT Srinivasa; Sandeep Kumar
Liquid Crystals 2017

12. A novel and sensitive hexadecyltrimethyalammoniumbromide functionalized Fe decoreated MWCNTs modified carbon paste electrode for the selective determiniation of Quercetin
Erady, Veera*; Mascarenhas, Ronald J*; Satpati, Ashis K*; Detriche, Simon*, Mekhalif, Zineb*; Delhalle*; Dhason A
Material Science and Engineering C **76**, 114-122, 2017

13. HI, star formation and tidal dwarf candidate in the Arp 305 system
Sengupta , Chandreyee*; Scott, T C*; Dwarakanath K S; + 3 co-authors
Monthly Notices of the Royal Astronomical Society **469**, 3629-3640, 2017

14. A hot X-ray filament between binary cluster A3017 and A3016
Parekh V., *et al.*
Monthly Notices of the Royal Astronomical Society, 2017

15. A study of halo and relic radio emission in merging clusters using the Murchi-son Widefield Array
George L T; Dwarakanath K S; +10 Co-authors
Monthly Notices of the Royal Astronomical Society **467**, 936, 2017

16. Indication of a massive circumbinary planet orbiting the low-mass X-ray binary MXB 1658-298
Jain, Chetana* ; Paul, Biswajit ; Sharma , Rahul* ; Jaleel, Abdul* ; Dutta, Anjan*
Monthly Notices of the Royal Astronomical Society **468**, L118, 2017

17. Clues to the origin of Fermi bubbles from OVIII/O VII line ratio
Sarkar, Kartick C
Monthly Notices of the Royal Astronomical Society **467**, 3544, 2017

18. Discotic liquid crystals with graphene: Supramolecular self-assembly to applications
Manish Kumar; Ashwathanarayana Gowda; Sandeep Kumar
Partical and Partical System Characterization 2017

19. N-term pairwise correlation inequalities, steering and joint measurability
Karthik H S ; Devi, Usha A R *; Tej, Prabhu J* ; Sudha, Rajagopal A K* ; Narayanan A
Physical Review A **95**, 052105, 2017

20. Equilibrium of fluid membranes endowed with orientational order
Alageshan, Jaya Kumar ; Chakrabarti, Buddhapriya *; Hatwalne, Yashodhan
Physical Review E **95**, 042806, 2017

21. Facile preparation of poly (Methylene blue) modified carbon paste electrode for the detection and quantification of catechin
Manasa G*; Mascarenhas, Ronald J*; Satpati, Ashis K*; D'souza Ozma*; Dhason A
Materials Science and Engineering C **73**, 552-561, 2017

22. Strongly interacting photons in one-dimensional continuum
Roy, Dibyendu ; Wilson C M *; Firstenberg, Ofer*
Review of Modern Physics, 2017 arXiv: 1603.06590

23. Critical features of nonlinear optical isolators for improved non-reciprocity
Roy, Dibyendu
arXiv:1611.05050, https://arxiv.org/abs/1611.05050

In Conference Proceedings

1. The nature and origin of ultra-high energy cosmic ray particles Biermann P L* ; Caramete, L I *; Fraschetti F* ; Gergely L A* ; Harms, B A *; Kun E* ; Lundquist J P* ; Meli, A* ; Nath, Biman B ; Seo, E S *; Stanev T* ; Becker-Tjus J *
Presented in the Vulcano Workshop 2016 "Frontier Objects in Astrophysics and Particle Physics"
22nd - 28th, May 2016. The proceedings will be published in electronic form in the Frascati Physics Series (arXiv: 1610.01183)

2. Changing dimensions of academic librarianship from ancient to digital era
Meera B M
Role of LIS Professionals in the Changing Academic Paradigm, Presidency University, Bangalore

3. Spin-sensitive photoassociation in Rb-87 BEC with spin and spin-momentum superposition dressed states
Blasing, David*$^{+}$; Wang, Su-Ju* ; Pérez-Ríos , Jesús* ; Li, Chuan-Hsun* ; Dutta, Sourav ; Greene, Chris * ; Chen*, Yong P
American Physical Society - 47th DAMOP Meeting, Rhode Island, U.S.A., May 23 – 27, 2016

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

Conferences Attended And Institutions Visited

Appendix II

Name	Conferences attended / Institutions visited	Title of paper/talk
Abir Sarkar	13th Asia-Pacific Symposium on Cosmology and Particle Astrophysics University of Sydney, Australia 28 November – 2 December 2016	Studying the effects of late forming dark matter in our universe (Skype talk)
	Astronomical Society of India Meeting Birla Institute of Scientific Research, Jaipur 6 – 10 March 2017	The effects of the small-scale behavior of dark matter power spectrum on CMB spectral distortion
Andal Narayanan	IEEE Conference on Recent Advances in Lightwave Technology Bangalore International Exhibition Center Bengaluru 21 September 2016	Quantum optics (*Invited*)
	Cochin Institute of Science and Technology Cochin 30 September – 2 October 2016	Introduction to quantum optics (*4 lectures*)
	RV College of Engineering Bengaluru 1 March 2017	Engineering quantum optics
Arun Roy	Sikkim University, Gangtok 17 October 2016	The fascinating anisotropic liquid states of bent rod like molecules
	The 23rd National Conference on Liquid Crystals Indian School of Mines, Dhanbad 7 – 9 December 2016	Pseudo-polar tilted smectic phases of bent rod-like molecules
	International Conference on Complex Fluids 2016 International Institute of Information Technology, Hyderabad 12 – 14 December 2016	Novel smectic phases of asymmetrically bent rod like molecules
	M.S. Ramaiah Institute of Technology Bengaluru 10 January 2017	Novel liquid crystalline phases of bent rod like molecules
Ashutosh Singh	Conference on Fundamental Problems of Quantum Physics International Centre for Theoretical Sciences Bengaluru 21 November – 10 December 2016	Manipulation of entanglement sudden death in an all-optical experimental set-up
Ashwathanarayana Gowda	26th International Liquid Crystal Conference Kent State University, USA 31 July – 5 August 2016	Ethylenedioxythiophene as a novel central unit for bent-core liquid crystals
	University of Colorado, USA 6 - 10 August 2016	Novel synthesis and characterisation of banana, discotic liquid crystals and nano-composites

	University of Texas, USA 11- 15 August 2016	Novel synthesis and characterisation of banana, discotic liquid crystals and nano-composites
	23rd National Conference on Liquid Crystals Indian School of Mines, Dhanbad 7 - 9 December 2016	Ethylenedioxythiophene (EDOT): Novel central unit for bent-core liquid crystals
Avinash Deshpande	Indian Institute of Science Education and Research, Trivandrum 2 - 3 May 2016	Fascinating life stories of pulsars
	Indian Institute of Space Science and Technology, Trivandrum 2 - 3 May 2016	
	Cochin University of Science and Technology Kochi 19 - 22 October 2016	
	Aryabhatta Research Institute of Observational Sciences, Nainital 3 - 7 December 2016	Fascinating life stories of pulsars
	10th International Olympiad on Astronomy and Astrophysics National Institute of Science Education and Research, Bhubaneswar 9 - 19 December 2016	
	ST-Radar User Workshop Cochin University of Science and Technology Cochin 7 - 10 February 2017	1.Radio astronomy basics 2.Radio astronomy with ST-Radar (*Invited*)
	DST-INSPIRE Program KIIT University, Bhubaneswar 18 - 19 February 2017	Fascinating life-stories of pulsars
	MVJ College of Engineering, Bengaluru 23 February 2017	1. Fascinating life-stories of pulsars 2. SWAN
	URSI-RCRS-2017 Conference National Atmospheric Research Laboratory Tirupati 1 - 4 March 2017	Sky watch array network: A strategic initiative (*Invited*)
Biman Nath	Isradynamics 2016 Ben-Gurion University of the Negev Israel 7 April 2016	Galactic outflows: physical mechanism
	Hebrew University, Israel 7 April 2016	Outflows from galaxies: shocks and surprises
	National Centre for Radio Astrophysics, Pune 18 November 2016	Fermi bubbles: the biggest shock in the sky
Biswajit Paul	Conference on The Future of Gravitational-wave Astronomy International Centre for Theoretical Sciences Bengaluru 6 - 7 April 2017	ASTROSAT-LAXPC: Some early results and prospects for GW astronomy

	Neighbourhood Astronomy Meeting Indian Space Research Organisation, Bengaluru 5 October 2016	X-ray pulsar observations with ASTROSAT-LAXPC
	Conference on 7 years of MAXI : Monitoring X-ray Transients RIKEN, Japan 5 - 7 December 2016	Early results from ASTROSAT and scientific prospects of POLIX
	Osaka University, Japan 9 December 2016	Indian Astronomy missions ASTROSAT and POLIX
	International Conference on Wideband Spectral and Timing Studies of Cosmic X-ray Sources Tata Institute of Fundamental Research Mumbai 10 - 13 January 2017	Tale of X-ray eclipses
	National Conference on Exploring the COSMOS North Bengal University, West Bengal 16 - 17 January 2017	Tale of X-ray eclipses
Buti Suryabrahmam	Microscopy Mela National Centre for Biological Sciences Bengaluru 25 - 26 September 2016	
Deepak Gupta	Statphys Kolkata IX Saha Institute of Nuclear Physics, Kolkata 13 - 16 December 2016	Fluctuation theorem for entropy production of a partial system in the weak coupling limit
	Indian Statistical Physics Community Meeting 2017 International Centre for Theoretical Sciences Bengaluru 17 - 19 February 2017	Fluctuation theorem for entropy production of a partial system in the weak coupling limit
Deepshika Malkar	The 23rd National Conference on Liquid Crystals Indian School of Mines, Dhanbad 7 - 9 December 2016	Molecular organization of bent core hockey stick shaped molecules in pseudo-polar tilted smectic phases
Dhason A	Workshop on Disciplinary Rules and Procedures Sterling Holiday Resort, Mussoorie 8 – 11 June 2016	
	Glass Apparatus for Distilling of Herbal Medicine Gandhigram Rural Institute, Dindigul 15 December 2016	
	18th National Seminar on Role of Scientific Glassblowing in Rural Development Gandhigram Rural Institute, Dindigul 16 – 17 December 2016	A simple and low cost Ultramicro electrode (Au, Pt) fabrication technique
Dibyendu Roy	Conference on Advanced Working Group on Many-Body Localisation University of Cambridge, UK 5 - 6 July 2016	

	Max-Planck Institute for the Physics of Complex Systems, Germany 7 - 22 July 2016	
Dwarakanath KS	SKA Scientific Conference Hotel Cidade de Goa, Goa 7 – 11 November 2016	
	Astronomical Society of India Meeting Birla Institute of Scientific Research, Jaipur 6 – 10 March 2017	
Gautam V Soni	Ramalingaswami Fellowship Conclave Indian Institute of Science Education and Research, Pune 4 - 6 January 2017	Epigenetic gene silencing by chromatin using nano-devices
	2017 Physical Science of Cancer Conference Gordon Research Conferences, USA 5 - 10 February 2017	Measuring whole cell stiffness using a novel microfluidic platform
	61st Biophysical Society Meeting Earnest N Morial Convention Center, USA 11 - 15 February 2017	Measuring whole cell stiffness using microfluidic platform
	Conference on DNA Physics Birla Institute of Technology and Science Pilani 9 - 11 March 2017	Nucleotide and nucleo-protein complexes detection using nanopore platform
Girish BS	Conference on CMB Spectral Distortions from Cosmic Baryon Evolution Raman Research Institute, Bengaluru 11 - 16 July 2016	
Gopala Krishna MR	34th Astronomical Society of India Meeting University of Kashmir, Srinagar 10 - 13 May 2016	1. X-ray Polarimeter POLIX: Signal processing electronics development 2. X-ray Polarimeter – POLIX: Design and development status 3. A large area photo-electron polarimeter technique: Experimental and simulation results
Hema Ramachandran	International Workshop on Complex Photonics 2017 Tata Institute of Fundamental Research Mumbai 22 - 24 January 2017	Imaging through fog and other scattering systems (*Invited*)
	International Conference on Complex Quantum Systems Bhabha Atomic Research Centre, Mumbai 20 – 23 February 2017	Observing coherent dynamics in a thermal collection of atoms (*Invited*)
Jacob Rajan	Conference on Institutional Digital Repository for National Digital Library Project Indian Institute of Science, Bengaluru 21 May 2016	

	Garuda National Partners Meet National Institute of Advanced Studies Bengaluru 8 - 9 September 2016	
	National Cyber Safety & Security Standards Summit Birla Institute of Technology and Science Hyderabad 17 - 18 February 2017	
	National Conference on Parallel Computing Technologies National Institute of Advanced Studies Bengaluru 23 - 24 February 2017	
Jagadeesh RV	67th Annual ISE Meeting International Society of Electrochemistry The Netherlands 21 - 26 August 2016	Enhanced electro – oxidation of ethanol in alkaline medium studied on Pd dispersed graphite and exfoliated graphite electrodes
	University of Limerick, Ireland 29 August - 1 September 2016	Adsorption kinetics studies of phosphonic acids and proteins onto functionalized Indium Tin Oxide surfaces
	University of Aberdeen, Aberdeen 2 - 4 September 2016	Adsorption kinetics studies of phosphonic acids and proteins onto functionalized Indium Tin Oxide surfaces
Janakee Raste	Astronomical Society of India Meeting Birla Institute of Scientific Research, Jaipur 6 - 10 March 2017	Analytically modelling early phase of EoR
Joseph Samuel	Bangalore Area Strings Meeting International Centre for Theoretical Sciences Bengaluru 25 - 27 July 2016	Wick rotation in the tangent space
	Prof. G. Rajasekaran Fest Chennai Mathematical Institute, Chennai 19 - 20 August 2016	Wick rotation in the tangent space
Kamini P A	CDN Live Cadence Allegro Technical Conference Hotel Park Plaza, Bengaluru 5 August 2016	
Karamveer Kaur	Neighbourhood Astronomy Meeting Indian Space Research Organisation, Bengaluru 5 October 2016	Secular collisionless instabilities in Keplerian stellar discs
	Astronomical Society of India Meeting Birla Institute of Scientific Research, Jaipur 6 - 10 March 2017	Secular instabilities of the stellar discs about massive black holes

Krishnamurthy S	Information Training Programme for Government Officers Centre for Development of Advanced Computing, Bengaluru 12 - 13 May 2016	
Kartick C Sarkar	Conference on Dynamical Processes in Space Plasma The Dead Sea Isrotel Hotel, Israel 3 - 10 April 2016	
	Tel-Aviv University and Wiezmann Institute Israel 4 - 13 April 2016	
	Max Planck Institute for Astrophysics, Germany 11 - 20 April 2016	
	34th Astronomical Society of India Meeting University of Kashmir, Srinagar 10 -13 May 2016	
	Heidelberg Institute of Theoretical Physics Germany 1 - 3 September 2016	
	Conference on Crossing the Rubicon: fate of gas flows in galaxies Teatro il Lavatoio, Italy 5 - 9 September 2016	
	Conference on Disks, Dynamos, and Data: Confronting MHD Accretion Theory with Observations University of California, USA 6 - 10 February 2017	
	University of California, USA 23 February 2017 6 March 2017 27 March 2017	
	Conference on Phenomena, Physics and Puzzles of Massive Stars and their Explosive Outcomes University of California, USA 20 - 24 March 2017	
Kumar Raviranjan	Workshop on Champ on Hand-on Experience in Radioastronomy Radio Astronomy Centre, Ooty 6 - 22 June 2016	
Lakshmi Saripalli	Meeting: Yugaantar - A Think Space for Young India Bhoomi College, Bengaluru 7 - 10 April 2016	
	Future of Liberal Arts and Science Education Conference Symbiosis School for Liberal Arts, Pune 16 - 18 May 2017	Liberal education for an 'Alternate System'

	Science and Monks Seminar Sarnath International Nyingma Institute Sarnath 21 - 23 November 2016	Public awareness of science
Madhavan Varadarajan	21st International Conference on General Relativity and Gravitation Columbia University, New York 10 - 15 July 2016	
	Lousiana State University, USA 19 July 2016	Propogation in polymer parameterized field theory
	Bangalore Area Strings Meeting International Centre for Theoretical Sciences Bengaluru 26 July 2016	A new Poisson bracket identity for gravity (or an excuse to review LQG!) (*Invited*)
	International Loop Quantum Gravity Seminar 13 September 2016	Propogation in polymer parameterized field theory (t*alk delivered by phone from RRI*)
	International Conference on Fundamental Problems of Quantum Physics International Centre for Theoretical Sciences Bengaluru 5 - 9 December 2016	A note on entanglement, entropy, coherent states and gravity (*Invited*)
	Delhi University, New Delhi 14 April 2016 27 December 2016	Entanglement entropy, gravity and coherent states (2 parts)
Madhavi S	Annual Technical User Conference CDNLIVE2016 Hotel Park Plaza, Bengaluru 9 August 2016	
Mani M	Centre for Nano and Soft Matter Sciences Bengaluru 3 July 2016	
Manjunath Kaddipujar	Symposium on Apps for Library and Information Services Karnataka State Library Association, Bengaluru 3 July 2016	
Manjunath M	Symposium on Apps for Library and Information Services Karnataka State Library Association, Bengaluru 3 July 2016	
	International Conference on Changing Landscape of Science and Technology Libraries 2017 Indian Institute of Technology, Gandhinagar 2 - 4 March 2017	
Mayuri S Rao	Conference on CMB Spectral Distortions from Cosmic Baryon Evolution Raman Research Institute, Bengaluru 11 – 16 July 2016	APSERa – Array of precision spectrometers for the epoch of recombination

	SKA Scientific Conference Hotel Cidade de Goa, Goa 7 – 11 November 2016	1. Outrigger antennas for global EoR with SKA – A dual role for SKA, science for the SKA generation 2.Erasing foregrounds for EoR science with SKA, science for the SKA generation
Meera BM	National Symposium on Re-vitalizing LIS Education and Research for the Present and Future and Alumni Meet Bangalore University, Bengaluru 14 May 2016	
	Regional (South-II)Workshop on Institutional Digital Repository for National Digital Library Project Indian Institute of Technology, Kharagpur 20 - 21 May 2016	
	Symposium on Apps for Library and Information Services Karnataka State Library Association, Bengaluru 3 July 2016	
	International Symposium on Electronic Thesis and Dissertations University of Lille, France 11 - 13 July 2016	Data intensive research at Raman Research Institute: A case study of challenges and perspectives employing questionnaire survey and ETD repository
	Nodal Officers Meet National Institute of Science Communication and Information, New Delhi 29 - 30 August 2016	Preservation and archiving of e-journals: a road map for Indian Library Consortium (*Invited*)
	National Conference on Women in Academic Institutions: Opportunities, Challenges and Constraints Sindhi College of Commerce, Bengaluru 9 February 2017	Women in academics: From mythology to modern age (*Keynote address*)
	National Conference on Role of LIS Professionals in the Changing Academic Paradigm Presidency University, Bengaluru 17 - 18 February 2017	Changing dimensions of academic Librarianship from ancient to digital era (*Keynote Lecture*)
	International Conference on Changing Landscape of Science and Technology Libraries 2017 Indian Institute of Technology, Gandhinagar 2 - 4 March 2017	Unconventional Library Services A case of best practices at the Raman Research Institute
Meera Thomas	International Conference on Soft Materials Malaviya National Institute of Technology Jaipur 12 – 16 December 2016	Polyelectrolyte induced swelling in a lamellar phase
Nagaraj MN	Workshop on SPSS Application on Data Analysis Tumkur University, Tumkur 21 January 2017	

Nagaraja HN	CDN Live Cadence Allegro Technical Conference Hotel Park Plaza, Bengaluru 5 August 2016	
	36th India International Trade Fair Pragathi Maidan, New Delhi 14 - 27 November 2016	
Paramesh Gadige	International Conference on Complex Fluids 2016 International Institute of Information Technology, Hyderabad 12 - 14 December 2016	Study of colloidal glass transition in polydisperse poly (Nisopropylacrylamide) microparticle suspensions (*Invited*)
	Indian Institute of Technology, Kanpur 1 April 2016	Dielectric spectroscopy
Pramod Pullarkat	Conference on Mechanical Forces in Cell Biology National Centre for Biological Sciences Bengaluru 4 - 6 October 2016	Myosin-II independent force generation by f-actin in axonal membrane tethers
Pratibha R	The 23rd National Conference on Liquid Crystals Indian School of Mines, Dhanbad 7 - 9 December 2016	Synchronization of conformational chirality in mixtures of achiral bent-core molecules (*Invited*)
Priyanka Singh	34th Astronomical Society of India Meeting University of Kashmir, Srinagar 10-13 May 2016	Suppression of galactic outflows by cosmological infall / circumgalactic medium
	Conference on From Wall to Web The Max Planck Institute for Astronomy, Berlin 24 - 29 July 2016	The prospects of detecting Sunyaev-Zel'dovich and X-ray signals from the circumgalactic medium
	Max Planck Institute for Astrophysics, Germany 30 July – 5 August 2016	The prospects of detecting Sunyaev-Zel'dovich and X-ray signals from the circumgalactic medium
	ETH, Switzerland 6 – 12 August 2016	
	Tata Institute of Fundamental Research Mumbai 5 - 11 January 2017	
	Astronomical Society of India Meeting Birla Institute of Scientific Research, Jaipur 6 - 10 March 2017	Constraints on the relation between the X-ray AGNs and host dark matter halo: potential role of eROSITA
Raghunathan A	International Conference on Cosmology and Astroscience 2017 Ethiraj College for Women, Chennai 8 – 10 February 2017	Recent advances in antenna technology for the detection of cosmological signal (*Invited*)
Raghunathan VA	National Chemical Laboratories Pune 14 June 2016	Electrostatic self-assembly of linear macroions

	International Conference on Complex Fluids 2016 International Institute of Information Technology, Hyderabad 12 - 14 December 2016	Hexatic phase of self-assembled micellar polymers (*Invited*)
	61st Department of Atomic Energy Solid State Physics Symposium Kalinga Institute of Industrial Technology Bhubaneswar 26 - 30 December 2016	Self-assembled structures of linear macroions (*Invited*)
Raj Prince	Astronomical Society of India Meeting Birla Institute of Scientific Research, Jaipur 6 - 10 March 2017	Long term study of the light curve of PKS 1510-089 in GeV energies
Ramesh B	Amrita Vishwa Vidyapeetham Bengaluru 30 April 2016	Viewing the cosmos
Ranjini Bandopadhyay	Yokohama Institute for Earth Sciences, Japan 12 April 2016	Microstructures and yielding of gel networks of charged anisotropic colloidal clay particles in aqueous suspensions
	Okinawa Institute of Science and Technology Japan 18 April 2016	A colloidal suspension as a model glass former: some recent results
	National Graduate Institute of Policy Research Japan 16 May 2016	Women's participation in science - women researchers in the next generation: a global young academy perspective
	G7 Science and Technology Ministers Summit Tsukuba International Congress Center, Japan 16 May 2016	Empowering women and young leaders in science, technology and industry (*Invited, Plenary*)
	Lecture-demonstration at the Summer Course for College Students Jawaharlal Nehru Planetarium Bengaluru 31 May 2016	Soft Matter: their flow and deformation (*Invited*)
	Delhi Public School, Bengaluru 23 August 2016	The flow and deformation of soft matter (*Invited*)
	Conference on Fractures and Plasticity Institute of Mathematical Sciences Chennai 4 - 7 January 2017	Aggregation and stability of anisotropic charged clay colloids in aqueous medium in the presence of salt (*Invited*)
	Faculty Development Programme on New Horizon in Soft Condensed Matter Physics for Interdisciplinary Research Ramaiah Institute of Technology, Bengaluru 9 - 14 January 2017	The curious case of soft matter (*Invited*)
	Indian Statistical Physics Community Meeting International Centre for Theoretical Sciences Bengaluru 17 February 2017	Study of the colloidal glass transition in suspensions of highly polydisperse poly(N-isopropylacrylamide) microparticles

	St. Joseph's College, Bengaluru 2, 9 and 23 March 2017	The physics of soft materials (3 lectures)
	Solvay Soft Matter Microsymposium Solvay Research and Innovation Center Vadodara 17 March 2017	The approach of colloidal suspensions towards kinetic arrest: some recent experimental results (*Invited*)
Reji Philip	SERC School on Lasers and Nonlinear Optics Pondicherry University, Pondicherry 4 - 5 April 2016	1. Ultrafast lasers 2. Basics of nonlinear optics
	The Second International Conference on Materials Science and Technology 2016 St.Thomas College, Pala 5 - 8 June 2016	Nonlinear optics of nanomaterials (*Invited*)
	GIAN Workshop on Nanotechnology: From fundamentals to practice Indian Institute of Science Education and Research, Thiruvananthapuram 16 June 2016	Nonlinear optics of nanomaterials
	The 2016 Source Workshop Hotel CASA 400, Amsterdam 7 - 9 November 2016	1. Laser produced highly ionized aluminum plasma for high harmonic generation 2. Enhancement of X-ray emission by double-pulse target ablation in a laser produced plasma
	Institut Catala de Nanociencia I Nanoteccnologia, Spain 10 – 11 November 2016	
	University of Naples Federico II, Italy 14 November 2016	Laser produced plasma experiments at the Raman Research Institute
	The fourth DAE-BRNS theme meeting on Ultrafast Science 2016 Bhabha Atomic Research Centre, Mumbai 24 - 26 November 2016	Time of flight dynamics of atomic and ionic species in an ultrafast laser produced copper plasma (*Invited*)
	National Seminar on Nanophotonics St. Thomas College, Trichur 10 January 2017	Introduction to nanophotonics (*Invited*)
	Optics-17: A Conference on Light National Institute of Technology, Calicut 9 - 11 January 2017	Ultrafast laser induced periodic surface structuring in silicon (*Invited*)
	National Photonics Symposium International School of Photonics Cochin University of Science and Technology Cochin 26 - 28 February 2017	Lacer induced surface structuring and applications (*Invited*)
Rishin PV	34th Astronomical Society of India Meeting University of Kashmir, Srinagar 10 - 13 May 2016	1.X-ray Polarimeter – POLIX: Design and development status 2.X-ray Polarimeter – POLIX: Signal processing electronics development 3.A large area photo-electron Polarimeter technique: Experimental and simulation results

Sadiq Rangwala	4th European Conference on Trapped Ions Waldhotel National, Switzerland 29 August – 2 September 2016	Using atom-cavity collective strong coupling to measure ion-atom collisions (*Invited*)
	Laboratoire Amie Cotton, Orsay 6 & 19 September 2016	1.Ion-Atom-Molecule-Cavity Experiments at RRI: Part I 2. Ion-Atom-Molecule-Cavity Experiments at RRI: Part II
	Laboratoire de Physique des Lasers Univercite Paris XIII 23 September 2016	Measurements on and with atom-cavity coupling
	Collage de France, Paris September 2016	
	Institute d'Optique, Orsay September 2016	
	Indian Institute of Technology, Kanpur 6 - 8 October 2016	Interactions in a trapped ion-atom system
	XXI National Conference on Atomic and Molecular Physics Physics Research Laboratory, Ahmedabad 3 - 6 January 2017	Origins to state of the art for trapped and cooled ion-atom mixtures (*Plenary talk*)
	Okinawa Institute of Science and Technology Japan 19 - 24 February 2017	The remarkable cooling of trapped ions by trapped atoms
	10th India - NUS Physics Symposium Indian Institute of Science, Bengaluru 26 - 28 February 2017	The remarkable cooling of trapped ions by trapped atoms
Sandeep Kumar	Indian Institute of Science, Bengaluru 18 April 2016	Supramolecular nanocomposites as advanced materials for opto-electronics
	Indian Institute of Science Education and Research, Mohali 16 May 2016	Playing with discs
	The International Conference on Materials Science and Technology 2016 St. Thomas College, Kerala 5 - 8 June 2016	Supramolecular nanocomposites as advanced materials for opto-electronics (*Invited*)
	Gauhati University, Assam 25 June 2016	
	Indian Institute of Technology, Kharagpur 12 July 2016	
	Faculty Development Program BMS College, Bengaluru 13 July 2016	Liquid crystalline nanocomposites as advanced materials for optoelectronics
	Siddaganga Institute of Technology, Tumkur 23 July 2016	

	The 26th International Liquid Crystal Conference Kent State University, USA 31 July – 5 August 2016	Supramolecular nanocomposites as advanced materials for opto-electronics
	Science Academies Lecture Workshop-New Horizons in Chemical and Biochemical Sciences Indian Academy College, Bengaluru 22 September 2016	Liquid Crystals: The intriguing fourth state of matter
	New Horizon College of Engineering Bengaluru 28 September 2016	Liquid Crystals: The intriguing fourth state of matter
	International Conference on New Scintillation on Materials Horizon M.J.P. Rohilkhand University Bareilly 21 - 23 October 2016	Supramolecular nanocomposites as advanced materials for opto-electronics (*Invited*)
	Birla Institute of Technology and Science, Pilani 25 November 2016	
	The 23rd National Conference on Liquid Crystals Indian School of Mines, Dhanbad 7 - 9 December 2016	Liquid crystals in photovoltaics: A new generation of organic photovoltaics (*Invited*)
	12th International Conference on Nanomolecular Electronics 2016 Kobe International Conference Center, Japan 14 - 16 December 2016	Discotic liquid crystals: Past, present and future (*Plenary*)
	Faculty Development Program Ramaiah Institute of Technology, Bengaluru 10 January 2017	The fascinating world of liquid crystals
	The 3rd Asian Conference on Liquid Crystals 2017 National Cheng Kung University, Taiwan 13 - 15 February 2017	Supramolecular nanocomposites as advanced materials for opto-electronics (*Plenary*)
	National Sun Yat-sen University, Taiwan 16 February 2017	Discotic nanocomposites
	National Chiao Tung University, Taiwan 17 February 2017	Liquid crystals in photovoltaics: A new generation of organic photovoltaics
	Vellore Institute of Technology, Vellore 25 February 2017	1.Liquid crystals and their nanocomposites 2.Discotic liquid crystals
Sanjay Kumar Behera	DM-glass Conference Jawaharlal Nehru Centre for Advanced Scientific Research, Bengaluru 29 - 30 April 2016	Study of the glass transition in suspensions of soft spherical colloidal particles with controllable polydispersity
	International Conference on Soft Materials Malaviya National Institute of Technology Jaipur 12 - 16 December 2016	Study of the glass transition in suspensions of soft spherical colloidal particles with controllable polydispersity
Sanjib Sabhapandit	National Institute of Science Education and Research, Bhubaneswar 26 - 27 April 2016	Fluctuations and large deviations in nonequilibrium systems (*Invited*)

	Bangalore School on Statistical Physics VII International Centre for Theoretical Sciences Bengaluru 1 - 15 July 2016	Preparatory lectures
	Conference on Nonequilibrium Statistical Physics of Complex Systems Korea Institute of Advanced Study, Korea 4 - 7 July 2016	Fluctuation theorem for entropy production of a partial system in the weak coupling limit (*Invited*)
Saptarishi Chaudhuri	10th India-NUS Physics Symposium Indian Institute of Science, Bengaluru 24 – 26 February 2017	A new quantum gas mixture experiment (*Invited*)
Siddhartha Gupta	Astronomical Society of India Meeting Birla Institute of Scientific Research Jaipur 6 – 10 March 2017	Lack of thermal energy in superbubbles: hint of cosmic rays?
Sourav Dutta	4th European Conference on Trapped Ions Waldhotel National, Switzerland 29 August – 2 September 2016	1.The atom-cavity collective strong coupling measurement of ion-atom collisions (*Invited*) 2.Experimental demonstration of cooling of low mass trapped ions by atoms of higher mass
	Conference on Fundamental Problems in Quantum Physics International Centre for Theoretical Sciences Bengaluru 21 November – 10 December 2016	Coupled atom-cavity system: a quantum sensor
	INSPIRE Faculty Monitoring-cum-Interaction Meet Chandigarh University, Mohali 10 - 11 February 2017	Cooling and non-destructive detection of ions in a hybrid atom-ion-cavity trap
Sreeja Sasidharan	Microscopy Mela National Centre for Biological Sciences Bengaluru 18 - 25 September 2016	
	International Conference on Soft Materials Malaviya National Institute of Technology Jaipur 12 - 16 December 2016	Nucleotide induced phase separation in lipid bilayers
Sridhar S	34th Astronomical Society of India Meeting University of Kashmir, Srinagar 10 -13 May 2016	The disruption of multiplanet systems through resonance with a binary orbit (*Plenary, Invited*)
	Inter-University Centre for Astronomy & Astrophysics, Pune 6 - 13 July 2016	1. Planets, stars and black holes 2. Stellar dynamics around a massive black hole (*2 talks*)
	Indian Institute of Science Education and Research, Pune 7 - 9 November 2016	Stellar dynamics and statistical mechanics
Srinivasa HT	International Conference on Material Science and Technology 2016 St. Thomas College, Kerala 5 - 8 June 2016	New azobenzene derived symmetric molecules synthesis and characterization for liquid crystal properties

Srivani KS	Conference on CMB Spectral Distortions from Cosmic Baryon Evolution Raman Research Institute, Bengaluru 11 - 16 July 2016	
Subhajit Bhar	Conference on Fundamental Problems in Quantum Physics 2016 International Centre for Theoretical Sciences Bengaluru 21 November - 10 December 2016	
Sumati Surya	Dublin Institute of Advanced Studies, Ireland 16 June – 5 July 2016	A Hartle-Hawking wave function in causal set quantum gravity
	21st International Conference on General Relativity and Gravitation Columbia University, New York 10 - 15 July 2016	The Hartle-Hawking wave function in causal set quantum gravity
	Bangalore Area Strings Meeting International Centre for Theoretical Sciences Bengaluru 25 - 27 July 2016	The scalar field propagator on a causal set (*Invited*)
	Conference on Fundamental Problems in Quantum Physics International Centre for Theoretical Sciences Bengaluru 21 November - 10 December 2016	Covariant observables in causal set quantum gravity (*Invited*)
	Third Lakshmi Raman Memorial Lecture Indian Institute of Technology, Madras Chennai 22 March 2017	Lightcones and order in quantum gravity
Supurna Sinha	Meeting on The Legacy of Emmy Noether International Centre for Theoretical Sciences Bengaluru 29 - 30 August 2016	
	Meeting on Fundamental Problems in Quantum Physics International Centre for Theoretical Sciences Bengaluru 21 November - 10 December 2016	
Surya Narayan Sahoo	International Conference on Quantum Foundations National Institute of Technology, Patna 17 - 21 October 2016	
	Conference on Fundamental Problems of Quantum Physics International Centre for Theoretical Sciences Bengaluru 21 November - 10 December 2016	
Sushil Dubey	Wilhelm and Else Heraeus-Seminar on Neuronal Mechanics Physikzentrum, Bad Honnef, Germany 17 - 19 August 2016	Mechanical responses of axonal cytoskeleton

	Conference on Mechanical Forces in Cell Biology National Centre for Biological Sciences Bengaluru 4 - 6 October 2016	Mechanical responses of neurons
	International Conference on Soft Materials Malaviya National Institute of Technology Jaipur 12 - 16 December 2016	
Syed Nomaan Ahmed	34th Astronomical Society of India Meeting University of Kashmir, Srinagar 10 - 13 May 2016	Building propagators in causal set quantum gravity
Urbasi Sinha	Laboratoire Aime Cotton, France 15 June 2016	A tale of three slits: From superposition to correlated qutrits (*Invited*)
	University de Cergy Pontoise, France 17 June 2016	A tale of three slits: From superposition to correlated qutrits (*Invited*)
	Institute for Quantum Optics and Quantum Information, Austria 20 June 2016	A tale of three slits: From superposition to correlated qutrits (*Invited*)
	University of Innsbruck, Austria 22 June 2016	A tale of three slits: From superposition to correlated qutrits (*Invited*)
	Conference on Formulating and Finding Higher Order Interference Perimeter Institute for Theoretical Physics Canada 3 -5 August 2016	Non zero experimental bound on third order interference within quantum theory (*Invited*)
	Workshop on Quantum Information National Physical Laboratories, New Delhi 19 August 2016	Non zero experimental bound on third order interference within quantum theory (*Invited*)
	SN Bose National Centre for Basic Sciences Kolkata 14h September 2016	A tale of three slits: From superposition to correlated qutrits (*Invited*)
	International Conference on Quantum Foundations 2016 National Institute of Technology, Patna 30 November - 4 December 2016	A tale of three slits: From superposition to correlated qutrits(*Invited*)
	Workshop on Quantum Information Science Pondicherry University, Pondicherry 17 - 18 February 2017	Fascinating world of photons, superposition and entanglement (*Invited*)
	National Science Day Indian Academy Degree College, Bengaluru 28 February 2017	Fascinating world of photons, superposition and entanglement (*Keynote lecture*)
Vani Hiremath	Symposium on Apps for Library and Information Services Karnataka State Library Association, Bengaluru 3 July 2016	
Vijayaraghavan D	4th International Conference on Nanostructured Materials and Nanocomposites Mahatma Gandhi University, Kottayam 10 - 12 February 2017	Self-assembled CNT-polymer hybrids in single walled carbon nanotubes dispersed aqueous triblock copolymer solutions (*Invited*)

Yashodhan Hatwalne	International Conference on Complex Fluids 2016 International Institute of Information Technology, Hyderabad 14 December 2016	The sectored morphology of polymer crystals (*Invited*)
	Jawaharlal Nehru Planetarium ium, Bengaluru	Thermodynamics
Yuvaraj AR	Indian Institute of Science, Bengaluru 3 June 2016	

Colloquia And Seminars

April	Vikram Khaire, Inter University Centre for Astronomy & Astrophysics, Pune *What drives the ionization state of hydrogen in the IGM: galaxies, QSOs or dark matter decay?*
	Manas Khan, University of California, USA *Colloids as model systems to study structural, dissipation and transport phenomena*
May	Lisa Glaser, The University of Nottingham, UK *Random non-commutative geometry*
	Tapashree Roy, Argonne National Laboratory, USA *Controlling light with nano-structured interfaces*
	Sujit Kumar Nath, Indian Institute of Science, Bengaluru *Origin of instability and plausible turbulence in astrophysical accretion disks and Rayleigh-stable flows*
	Gopalakrishna CR, Texas Tech University, USA *Highly sensitive, liquid crystal based sensor for chemical threat agent*
	Prosenjit Singha Deo, SN Bose National Center for Basic Sciences, Kolkata *Wildlife around a unique city*
	Sonali Rohiwal, D.Y.Patil University, Kolhapur *Incorporation of drug loaded graphene oxide-polymeric nanohybrid systems into polymeric electrospun nanofibers to accelerate wound healing*
	Padmanabhan G, Indian Institute of Science, Bengaluru *Translational scenario of biomedical research in India*
	Prosenjit Singha Deo, SN Bose National Center for Basic Sciences, Kolkata *Charge and spin density waves: Quasi one dimension to two dimensions*
	Jayan Thomas, The University of Central Florida, USA *Electrical cables for energy storage*
	Paul C.H. Li, Simon Fraser University, BC Canada *The use of nanoparticles to assist cellular and nucleic acid assays*
	Sankar Davuluri , Beijing Computational Science Research Center, China *Absolute rotation detection with quantum coherence and optomechanics*
	Jaswant K Yadav, Delhi University, New Delhi *FRBs: Blasts of radio waves from deep space*
June	Krishnamohan Parattu, Inter-University Center for Astronomy and Astrophysics, Pune *Variational principle for gravity with null boundaries*
	Soma Venugopal Rao, University of Hyderabad, Hyderabad *Raman spectroscopy for explosives detection*
	Sayantan Majumdar, The University of Chicago, USA *Encoding mechano-memories in F-actin networks*

June	Deepak Pandey, Universite Bordeaux, France *Bose-Einstein condensates and towards the coherence preserving measurements in a non-degenerate cavity* Kandaswamy Subramanian, Inter-University Centre for Astronomy & Astrophysics, Pune *Challenges in understanding cosmic magnetism* Chandreyee Maitra, CEA Saclay, France *A quest for young and energetic pulsars in the SMC: The case of IKT 16 & AX J0043-737* Ramanath Cowsik,Washington University, USA *High energy interstellar positrons & antiprotons – Relevance to cosmic ray and dark matter studies*
July	Ravi P Rau, Louisiana State University, USA *Stability at saddles of potentials* Anugrah Singh, Indian Institute of Technology, Guwahati *Effect of non-hydrodynamic forces on the rheology of dense suspensions* Ravi P Rau, Louisiana State University, USA *Studying parrots in Australia and Patagonia, plus astronomical knowledge of aboriginal peoples* Abhilasha Singh *Phase transition properties of ferroelectric and antiferroelectric liquid crystals* Rakhee Kushwah, ISRO Satellite Centre, Bengaluru and University of Calicut, Calicut *Studies on GEM based soft X-ray polarimeter* Rajaram Nityananda, Azim Premji University, Bengaluru *Conical refraction revisited* Bharat Ratra, Kansas State University, USA *The 'Standard' model of cosmology … and open questions* *Cosmological seed magnetic field from inflation* Sreenath Vijayakumar, Louisiana State University, USA *Evolution of primordial perturbations through an anisotropic quantum bounce*
August	Nampoori VPN, Cochin University of Science and Technology, Cochin *Group theory I* *Group theory II* *Spectroscopic applications of Group theory* *Spectroscopic applications of Group Theory II* Kinjalk Lochan, Indian Institute of Science Education and Research, Trivandrum *Information retrieval from black holes: Quantum correlations in non-vacuum distortions* Bijoy Daga, Saha Institute of Nuclear Physics, Kolkata *Phase separation transition and spatial correlations of reconstituting k-mers in one dimension* Anosh Joseph, University of Cambridge, UK *Quantum black holes and gravity from the lattice* Srikanth Sastry, Jawaharlal Nehru Centre for Advanced Scientific Research, Bengaluru *The yielding transition in amorphous solids*

August	Sayantan Majumdar, University of Chicago, USA *Encoding mechano-memories in F-actin networks*
	Nidaghatta Lingannaiah Gangadhar, Bengaluru *Educate - Vaccinate - Eliminate rabies, How much is Bangalore equipped ?*
September	Amit Kumar Majhi, Indian Institute of Science, Bengaluru *Investigations of electroporation physics using optically transparent polymer devices and molecular dynamics simulations*
	Lab Saha, Nicolaus Copernicus Astronomical Center, Poland *The fan-beam pulsar emission model: Polarization and precession driven pulse evolution*
	Brajesh Gupt, The Pennsylvania State University, USA *Quantum gravity, very early universe and the cosmic microwave background*
	Seema Satin, University of Maryland, USA *Noise kernel for self similar Tolman Bondi Metric: Fluctuations at Cauchy Horizon*
October	Venkatesan Iyer K, Max Planck Institute of Molecular Cell Biology and Genetics, Germany *Mechanical tension regulates the turnover of E-Cadherin during drosophila pupal wing morphogenesis*
	Neha Topnani, University of Warsaw, Poland *Hybrid materials based on liquid crystalline polymers and gels*
November	Balachandran A P, Syracuse University, USA *Algebraic quantum physics*
	Ashoke Sen, Harish-Chandra Research Institute, Allahabad *String theory: Past and present*
	Sayan Biswas, Bose Institute, Kolkata *Production scenario and flux of galactic strangelets*
	Suvodip Mukherjee, Inter University Centre for Astronomy & Astrophysics, Pune *Cosmic anomaly and its implications*
	Vivek Vyas, Institute of Mathematical Sciences, Chennai *Topological conservation laws*
	Kshitij Thorat, Rhodes University, South Africa *Morphological classification of extended radio source using machine learning techniques*
	Baladitya Suri, Chalmers University of Technology, Sweden *Artificial atoms interacting with photons and phonons*
	Yuri Shchekinov, Lebedev Physical Institute, Moscow *Russian space observatory "Millimetron" (Spekr-M)*
December	Drummond Fielding, University of California, Berkeley *The impact of star formation driven galactic winds on the circumgalactic medium*

December	Daniel Sudarsky, National Autonomous University of Mexico, Mexico *A novel approach to diffusing the black hole information paradox*
	Soumen Basak, Università Degli Studi Di Padova, Italy *The Universe – as seen by Plank*
January	Sibasish Laha, Queen's University, UK *Quasar evolution and outflows in X-ray*
	Abhishek Kumar Singh, Jawaharlal Nehru University, New Delhi *Relaxation in orientationally disordered phase of hexa-substituted benzenes*
	Vikram Rana, California Institute of Technology, USA *CZT pixel detectors onboard NuSTAR and hard X-ray characteristics of ULXs*
	Fabien Bretenaker, CNRS-Université Paris Sud-ENS Paris Saclay, France *Coherent population oscillations in an atomic vapour at room temperature: light storage, phase sensitive amplification, squeezing?*
	Francesco Sciortino, Universita' di Roma, Italy *Physics with DNA-made nanoparticles*
	Projjwal Banerjee, Shanghai Jiao Tong University, China *Did a low-mass supernova trigger the formation of the solar system? Clues from stable isotopes and 10Be*
	Pepijn W.H. Pinkse, University of Twente, The Netherlands *Quantum-secure authentication and adaptive quantum optics*
	Rao DVGLN, University of Massachusetts, USA *Photonic applications with a protein complex*
February	Nissim Kanekar, National Centre for Radio Astrophysics, Pune *Cold gas in high-redshift galaxies*
	Prashanth Mohan, Shanghai Astronomical Observatory, China *SKA work directions and AGN studies*
	Jincy Devasia, Raman Research Institute, Bengaluru *Accreting X-ray pulsars in outbursts: past studies and future plans with Astrosat*
	Mainpal Rajan, Inter-University Centre for Astronomy & Astrophysics, Pune *X-ray/UV/Optical variability in Seyfert 1 galaxies*
	Satya Sainadh U, Griffith University, Australia *Attoclock using atomic hydrogen*
	Dieckmann K, National University of Singapore, Singapore *Ultracold molecules, ubi estis*? *where are you?*
March	Girish Kulkarni, Institute of Astronomy and Kavli Institut of Cosmology Cambridge, UK *Revealing 13 billion years of thermal evolution of the universe*
	Mutsumi Sugizaki , RIKEN, Japan *MAXI 7 years highlights and in-orbit instrument performance*

March	Alamgir Karim, The University of Akron, USA *Directed assembly of block copolymer and nanoparticle thin films for functional applications* Ayush Agrawal, Indian Institute of Science, Bengaluru *Pore forming toxins: Unraveling oligomerization pathways and related kinetics* Sabyasachi Bhattacharya, Ashoka University, Haryana *Disordered and driven soft and athermal matter: what is special about them?* Nachiketa Chakraborty, Max-Planck-Institut fur Kernphysik Germany *Novel observables in multiwavelength astronomy* Umesh V Waghmare, Jawaharlal Nehru Centre for Advanced Scientific Research, Bengaluru *Design of materials with computer simulations based on quantum mechanics and machine learning* Tevian Dray, Oregon State University, USA *The geometry of relativity, & piecewise conserved quantities* Corinne Manogue, Oregon State University, USA *Using geometric reasoning to teach vector calculus in mathematics and physics* Tevian Dray,Oregon State University, USA *Using geometric reasoning to teach vector calculus in mathematics and physics* James Unwin, University of Illinois, USA *New approaches to dark matter* Shrinivas Venkataraman, Institute of Bioengineering and Nanotechnology, Singapore *Functional aliphatic polycarbonates: Syntheses, aqueous self-assembly and biomedical applications* Asif Iqbal Ahangar, University of Kashmir, J&K *An end to ICM preheating?* Sarma DD, Indian Institute of Science, Bengaluru *Attraction of magnetism*

Conference: CMB Spectral Distortions From Cosmic Baryon Evolution

11 July 2016	Colin Hill - *y-distortions from low-z universe* Jens Chluba - *CMB distortions as a probe of inflation and particle physics* Rishi Khatri - *Y and mu fluctuations* Jose-Alberto Rubino-Martin - *Recombination spectrum – atomic physics that determine the signal and recent developments* Eric Switzer - *PIXIE* Mayuri Sathyanarayana Rao - *APSERa* Jack Singal -*ARCADE* Subodh Patil – Discussion - *What science may we expect with next generation CMB spectral measurements? From space? From ground?*

12 July 2016	Shiv Sethi - *Current constraints from CMB + structure formation observations*
	Tirth Roy Chaudhury - *Early structure formation and first stars, galaxies: Reionization constraints after Planck-15*
	Jeff Peterson - *Oversampled aperture arrays*
	Anastasia Fialkov - *Monopole 21-cm signal*
	Leon Koopmans - *21-cm power spectrum from Cosmic Dawn & Reionization*
	Eric Switzer - *Global foreground cleaning and intensity mapping*
	Raul Monsalve - *EDGES*
	Jeff Peterson - *SCIHI*
	Marcin Sokolowski - *BIGHORNS*
	Lincoln Greenhill - *LEDA*
	Saurabh Singh - *SARAS 2*
	Abhirup Datta - *DARE*
14 July 2016	Tuhin Ghosh - *Polarized dust emission*
	Subir Sarkar - *Galactic & extragalactic synchrotron foregrounds*
	Jack Singal - *Unaccounted isotropic radio backgrounds*
	Marcin Sokolowski / Abhirup Datta - *Ionosphere*
	Chris Sheehy - *Atmosphere – including lines*
	Aaron Chippendale - *RFI – sites from earth to the far side of the moon*
	Mathieu Remazeilles (remote) - *SZ foregrounds*
	Xuelei Chen (remote) - *21-cm intensity mapping in the post reionization era*
	Tejaswi Venumadhav - *Primordial magnetic fields in the cosmic dawn epoch*
	Jose-Alberto Rubino-Martin - *The QUIJOTE experiment: Latest results*
	Adrian Liu - *Foreground separation in Global 21-cm experiments*
	Rennan Barkana - *Constraints on cosmology from Global 21-cm and other observables*
	Jens Chluba - *Modelling uncertainties: CMB distortions*
15 July 2016	Udaya Shankar - *Photon-starved versus photon-rich spectrometers – FTS & voltage sampling spectrometers*
	Aaron Chippendale - *Spectral radiometers – antenna, receiver, digital spectrometer – simplicity/calibration/spurious additives, etc.*

	Nipanjana Patra - *Pulse calibration* Lincoln Greenhill - *Outriggers* Ravi Subrahmanyan - *Interferometers for global signals* Leon Koopmans, - *Interferometers for 21-cm power spectrum* Harish Vedantham -*Moon block experiments* S Seetha - *ISRO space physics missions to date* M Annadurai - *ISRO space physics missions – plans and prospects for future space physics missions* Subir Sarkar and Siddharth Malu - *Conference summary* Rishi Khatri & Tarun Souradeep - *Discussion on space missions for CMB spectral distortions*

Workshop on Statistical Physics

5 - 9 Dec 2016	Satya Majumdar, University of Paris, France - *Random matrices meet cold atom* David Dean, University of Bordeaux, France - *Diffusion in complex and random media*
6 - Dec 2016	Herbert Spohn, Technical University of Munich, Germany - *Six-vertex model at its conical (KPZ) point*

RRI Science Forum

Appendix – IV

April	Biswajit Paul *The black hole that was not*
May	Raghunathan A *Breaking the reciprocity property of antennas through spatiotemporal modulation*
	Paramesh Gadige *Cooperative phenomena in glass forming liquids*
June	Avinash Deshpande *A repeating fast radio burst*
	Reji Philip *Extreme nonlinear optics: High harmonic and attosecond pulse generation from intense laser-matter interaction*
July	Viral Parekh *GaLactic and Extragalactic All-sky Murchison Widefield Array (GLEAM) survey: A low-frequency extragalactic catalogue*
August	Mayuri S Rao *Synaesthesia—A window into perception, thought and language*
September	Andal Narayanan & Athul Vinu *Resonance fluorescence from an artificial atom in squeezed vacuum*
	Saptarishi Chaudhuri *Quantum gases with long-range interactions*
October	Joseph Samuel *Circling exceptional points*
	Dibyendu Roy *Squeezed-light spin noise spectroscopy*
November	Sourav Dutta *A microscopic friction emulator*
	Sanjukta Roy *Quantum gases in Flatland: Berezinskii–Kosterlitz Thouless crossover in a trapped atomic Bose gas*
January	Mayuri S Rao *A terrestrial planet candidate in a temperate orbit around Proxima Centauri*
March	Abir Sarkar *The dark matter: It's dark, it's dominating and it's demanding!!*

Visitors

Appendix – V

Asha K *Kuvempu University, Shimoga*	1 Apr - 27 May 2016 8 - 31 Oct 2016 5 - 8 Jan 2017
Vikram Khaire *Inter-University Centre for Astronomy & Astrophysics, Pune*	1 - 2 Apr 2016
Dipankar Home *Bose Institute, Kolkata*	3 - 15 Apr 2016
Manojendu Chaudhuri *Mumbai University, Mumbai*	1 - 5 Apr 2016
Lisa Glaser *The University of Nottingham, UK*	25 Apr - 7 May 2016
Fabien Bretenaker *CNRS Laboratoire Aime Cotton, France*	1 - 14 May 2016 9 - 20 Jan 2017
Tapashree Roy *Argonne National Laboratory, USA*	2 - 3 May 2016
Nairit Das *Indian Institute of Technology, Kharagpur*	1 - 31 May 2016
Pragati Pradhan *North Bengal University, Darjeeling*	8 - 29 May 2016 25 Sep - 6 Nov 2016
Sujit Kumar Nath *Indian Institute of Science, Bengaluru*	9 May 2016
Ginson P Joseph *St. Thomas College, Kerala*	10 - 11 May 2016 18 - 20 Nov 2016
Gopalakrishna CR *Texas Tech University, USA*	11 - 15 May 2016
Prosenjit Singha Deo *S N Bose National Center for Basic Sciences, Kolkata*	15 - 24 May 2016 14 - 20 Nov 2016
Kishore Sridharan *National Institute of Tehcnology, Surathkal*	17 - 20 May 2016 10 - 12 Aug 2016
Krishnamohan Parattu *Inter-University Centre for Astronomy & Astrophysics, Pune*	1 Jun 2016
Kandaswamy Subramanian *Inter-University Centre for Astronomy & Astrophysics, Pune*	21 - 29 Jun 2016
Radhakrishnan AV *National University of Singapore, Singapore*	24 Jun - 1 Oct 2016

Jayan Thomas *The University of Central Florida, USA*	26- 28 May 2016
Jaswant Yadav *Delhi University, New Delhi*	30 May - 1 Jun 2016
Sujay Mate *Indian Institutes of Science Education and Research, Pune*	1 - 30 Jun 2016
Anders Kastberg *Universite Nice Sophia Antipolis, France*	9 - 27 Jun 2016 15 Jan - 31 Mar 2017
Soma Venugopal Rao *University of Hyderabad, Hyderabad*	12 - 14 Jun 2016
Cowsik R *Washington University, USA*	16 Jun - 4 Jul 2016
Chandreyee Maitra *CEA Saclay, France*	17- 25 Jun 2016
Deepak Pandey *Universite Bordeaux, France*	17- 25 Jun 2016
Sankar Davuluri *Beijing Computational Science Research Centre, China*	20 - 21 Jun 2016
Ravi P Rau *Louisiana State University, USA*	28 Jun - 17 Jul 2016
Aru Beri *Indian Institute of Technology, Ropar*	1- 7 Jul 2016
Rakhee Kushwah *ISRO Satellite Centre, Bengaluru & University of Calicut, Kerala*	18 Jul 2016
Rajaram Nityananda *Azim Premji University, Bengaluru*	22 Jul 2016
Bharat Ratra *Kansas State University, USA*	28 - 29 Jul 2016
Nampoori VPN *Cochin University of Science and Technology, Cochin*	1- 3 Aug 2016
Sreenath Vijayakumar *Louisiana State University, USA*	1- 2 Aug 2016
Kinjalk Lochan *Indian Institute of Science Education and Research, Trivandrum*	7- 10 Aug 2016
Anosh Joseph *Department of Applied Mathematics and Theoretical Physics, Cambridge, UK*	15 - 18 Aug 2016

Jijil J J Nivas *University of Naples, Italy*	17 Aug -10 Sept 2016 19 Sep - 26 Oct 2016
Nidaghatta L Gangadhar *Project Directorate on Animal Disease Monitoring and Surveillance, Bengaluru*	26 Aug 2016
Rahul Sharma *Delhi University, New Delhi*	1 Sep - 31 Oct 2016
Sujata Tarafdar *Jadavpur University, Kolkata*	13 -16 Sep 2016
Subhabrata Majumdar *Tata Institute of Fundamental Research, Mumbai*	13 – 19 Sep 2016
Lab Saha *Nicolaus Copernicus Astronomical Centre, Poland*	20 Sep - 1 Oct 2016
Brajesh Gupt *The Pennsylvania State University, USA*	25 – 28 Sep 2016
Seema Satin *University of Maryland, USA*	30 Sep 2016
Neha Topnani *University of Warsaw, Poland*	4 - 5 Oct 2016
Balachandran AP *Syracuse University, USA*	4 Oct - 4 Nov 2016
Gulab Chand Dwangan *Inter-University Centre for Astronomy & Astrophysics, Pune*	9 - 13 Oct 2016
Smijesh N Achary *Griffith University, Brisbane*	23 - 25 Oct 2016 18 Nov 2016
Kavya H Rao *Griffith University, Brisbane*	23 - 25 Oct 2016 18 Nov 2016
Aditya Dharmadhikari *Tata Institute of Fundamental Research, Mumbai*	25 - 27 Oct 2016
Jayashree Dharmadhikari *Tata Institute of Fundamental Research, Mumbai*	25 – 27 Oct 2016
Mark Dijkstra Institute of Theoretical Astrophysics, Norway	6 - 9 Nov 2016
Sayan Biswas *Bose Institute, Kolkata*	7 - 27 Nov 2016
Suvodip Mukherjee *Inter-University Centre for Astronomy & Astrophysics, Pune*	9 - 11 Nov 2016

Vivek Vyas *Institute of Mathematical Sciences, Chennai*	13 – 16 Nov 2016
Kshitij Thorat *Rhodes University, South Africa*	14 – 18 Nov 2016
Yuri Shchekinov *Lebedev Institute, Russia*	7 Nov - 5 Dec 2016
Rafael D Sorkin *Perimeter Institute, Canada*	17 - 25 Nov 2016
Baladitya Suri *Chalmers University of Technology, Sweden*	21 Nov 2016
Satya Majumdar University of Paris, France	23 Nov - 24 Dec 2016
David Dean University of Bordeaux, France	30 Nov - 12 Dec 2016 18 - 22 Dec 2016
R Rajesh *Institute of Mathematical Sciences, Chennai*	1 - 2 Dec 2016
David Rideout *University of California, San Diego, USA*	1 - 21 Dec 2016
Herbert Spohn *Technical University of Munich, Germany*	6 Dec 2016
Daniel Sudarsky *National Autonomous University of Mexico, Mexico*	9 - 15 Dec 2016
Praveen *Indian Institute of Space Science and Technology, Trivandrum*	10 - 15 Dec 2016
Fatemeh Ahmadi *Buein Zahra Technical University, Iran*	10 - 16 Dec 2016
Will Cunningham *Northeastern University, USA*	11 - 21 Dec 2016
Dionigi Benincasa *Perimeter Institute, Canada*	12 - 23 Dec 2016
Soumen Basak *Università degli Studi di Padova, Italy*	18 - 21 Dec 2016
Yasaman Yazdi *Perimeter Institute, Canada*	18 - 24 Dec 2016

Nosiphiwo Zwane *Perimeter Institute, Canada*	19 - 24 Dec 2016
Aru Beri *Southampton University, UK*	25 Dec 2016 - 9 Jan 2017
Avni Parmar *Pune University, Pune*	29 Dec 2016 - 6 Jan 2017
Sibasish Laha *Queen's University, UK*	1 - 4 Jan 2017
Mahadev Pandge *Dayanand Science College, Maharashtra*	11 - 17 Jan 2017
Jihad R. Touma *American University of Beirut, Lebanon*	6 - 20 Jan 2017
Vikram Rana *Caltech University, USA*	15 - 18 Jan 2017
Abhishek Kumar Singh *Jawaharlal Nehru University, New Delhi*	16 - 17 Jan 2017
Pepijn W.H. Pinkse *University of Twente, The Netherlands*	27 Jan 2017
Rao DVGLN *University of Massachusetts, USA*	28 - 31 Jan 2017
Nissim Kanekar *National Centre for Radio Astrophysics, Pune*	13 - 15 Feb 2017
Rajesh R *Institute of Mathematical Sciences, Chennai*	15 - 17 Feb 2017
Prashanth Mohan *Shanghai Astronomical Observatory, China*	16 - 17 Feb 2017
Vanessa Rodrigues *Manipal University, Manipal*	16 Feb - 2 Mar 2017
Mainpal Rajan *Inter-University Centre for Astronomy & Astrophysics, Pune*	19 - 22 Feb 2017
Arpita Roy *Australian National University, Sydney*	19 Feb - 3 Mar 2017
Satya Sainadh U *Griffith University, Australia*	20 - 28 Feb 2017
Mutsumi Sugizaki *RIKEN, Japan*	21 - 25 Feb 2017 1 - 2 Mar 2017

Amitabh Virmani *Institute of Physics, Bhubaneshwar*	23 - 24 Feb 2017
Kai Dieckmann *National University, Singapore*	22 - 24 Feb 2017
Girish Kulkarni *University of Cambridge, UK*	1 - 2 Mar 2017
Nazma Islam *Nicolus Copernicus Astronomical Centre, Poland*	11 - 17 Mar 2017
Sabyasachi Bhattacharya *Ashoka University, Haryana*	14 - 15 Mar 2017
Nachiketa Chakraborty *Max Planck Institute für Kernphysik, Germany*	15 - 18 Mar 2017
Shrinivas Venkataraman *Institute of Bioengineering and Nanotechnology, Singapore*	27 - 28 Mar 2017
Mukukeshan Vadakke Matham *Nanyang Technological University, Singapore*	28 Mar 2017

Visiting Students' Programme

Appendix – VI

Mentor	Students			
Andal Narayanan	Sayali Shevate	Sandeep N R	Charudatta Manwatkar	
Arun Roy	Elizabeth Joseph	Rishabh Shankar		
Biman Nath	Pushpita Das			
Deshpande A A	Akshita Gupta	Gaurav R S Tomar	Samina Mansuri	Tasha Gautam
	Anjana Kudva	Jigishakumari V	Shivam Arora	Tousif Islam
	Bhavishya C P	Pallavi M R	Sourita Saha	
Dibyendu Roy	Pooja Manasi	Nimba Oshnik Pandey	Aparna Sankar	
Dwarakanath K S	Avni Parmar			
Gautam Soni	Eshita Paul	Koushik S	Mahesh B L	Manohara M
	Monica Thankur	Ritesh Soni		
Hema Ramachandran	Rohit Bhatt	Vittala	Mani Kumar T	Ashok Kumar
	Reshma Ravi	Sukanya Mahapatra	G N Rameshwara	Anjan Kumar
	Ramana Reddy R	Mary Ida Melody K S	Binodbihari Panda	
Nayantara Gupta	Vaishnavi Kanamarlapudi	Partha Pratim Basumallick		
Pramod Pullarkat	Amal Alex	Lakshmi P S	Shruti Shirol	
	Bhumika Singh Rathore	Aniruddha Upadhye		
Pratibha R	Prutha Raj	Saranya Narayanan	Smruti Rekha M	
Ramesh B	Ashwini P	Guillaume Di Scala	Naimahmed Nesaragi	Rohit K A
	Chandrashekar M	Swaroop Jois K S	Neha Vinayak Thigala	Harshini S
	Anushree J Ranka			
Ranjini Bandopadhyay	Vipin Agrawal	Sreelakshmi M	Romil Audhkhasi	Jannet Joy
	Tonmoy Gogoi			
Raghunathan A	Akhil Reddy	Amarnath Reddy	Kshitij Sadasivan	Varun P
Ravi Subrahmanyan	Anisha Kadri	Karthik Thalambeti	Sweekruth Srinivas	
Ruckmongathan T N	Manogna S			

Mentor	Students			
Reji Philip	Alina Peetan Jyothis Thomas	Amrutha K Nithin Joy	Arya J.S.	Haritha M
Sumati Surya	Apurva Dhingra	Simran Singh		
Shiv Sethi	Avinash			
Saptarishi Chaudhuri	Sutapa Ghosh	Neema Prakash		
Sandeep Kumar	Himanshu Sehgal	Kavita R Rathod	Shalaka Varshney	Litwin Jacob
Urbasi Sinha	Anurag Saha Roy Rakshita R M	Gareeyasee Saha	Nandini S G	Neha K Naskar

RAMAN RESEARCH INSTITUTE
BENGALURU

Audited Statements of Accounts
2016-2017

G.R. VENKATANARAYANA
CHARTERED ACCOUNTANTS
No. 618, 75th Cross, 6th Block, Rajajinagar, Bangalore-560 010.
Ph: 23404921 / 64537325
Email: grvauditor@gmail.com/ 1grvenkat@gmail.com

Partners :
CA. G.R. Venkatanarayana, B.Com., F.C.A.,
CA. G.S. Umesh, B.Com., F.C.A.,
CA. Venugopal N. Hegde, B.Com., F.C.A.,

AUDITOR'S REPORT

TO THE MEMBERS OF RAMAN RESEARCH INSTITUTE, BANGALORE

We have audited the financial statements of the **"RAMAN RESEARCH INSTITUTE"**, Sir C V Raman Avenue, Sadashivanagar, Bangalore – 560080 which comprise of Balance sheet as at 31st March 2017, the Income & Expenditure Account for the year ended and the Receipts and Payment account for the year ended on that date annexed thereto. These financial statements are the responsibility of the management of Raman Research Institute. Our responsibility is to express an opinion on these financial statements based on our audit.

We conducted our audit in accordance with auditing standards generally accepted in India. Those standards require that we plan and perform the audit to obtain reasonable assurance about whether the financial statements are free of material misstatement. An Audit includes examining, on a test basis, evidence supporting the amounts and disclosures in the financial statements. An audit also includes assessing the accounting principles used and significant estimates made by Management as well as evaluating the overall financial statements presentation. We believe that our audit provides reasonable basis for our opinion.

We report that:

1. We have obtained all the information and explanations, which to the best of our knowledge and belief were necessary for the purpose of our audit.

2. In our opinion proper books of accounts as required by law have been kept by the Raman Research Institute so for as it appears from our examination of those books.

3. The Balance Sheet, Income and Expenditure Account and Receipts and Payment account dealt with by this report are in agreement with the books of account.

4. The Balance Sheet and Income and Expenditure Account dealt with by this report are prepared in accordance with the Accounting Standards issued by the Institute of Chartered Accountants of India.

.....2

G.R. VENKATANARAYANA Chartered Accountants BANGALORE

5. In our opinion and to the best of our information and according to the explanations given to us and subject to notes on accounts and our qualifications in para 4 above, the said accounts give a true and fair view in conformity with the accounting principles generally accepted in India:

   a) In the case of Balance Sheet, of the state of affairs of the Raman Research Institute as at March 31, 2017; and

   b) In the case of Income and Expenditure Account, of the excess of Expenditure over Income for the year ended on that date.

For M/s G R Venkatanarayana
Chartered Accountants
Firm Regn. No. 004616S

(G R Venkatanarayana)
Partner
Membership No. 018067

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

Place: Bangalore
Date: 03.07.2017

RAMAN RESEARCH INSTITUTE, BANGALORE
BALANCE SHEET AS AT 31ST MARCH 2017

(Amount in INR)

CORPUS/CAPITAL FUND AND LIABILITIES	Schedule	Current Year	Previous Year
Corpus/Capital Fund	1	101,97,11,772	101,64,55,150
Reserves & Surplus	2	-	-
Earmarked & Endowment Funds	3	55,06,03,391	49,10,15,247
Secured Loans & Borrowings	4	-	-
Unsecured Loans & Borrowings	5	-	-
Deferred Credit Liabilities	6	-	-
Current Liabilities & Provisions	7	1,95,90,914	1,65,78,598
TOTAL		**158,99,06,077**	**152,40,48,995**
ASSETS			
Fixed Assets	8	93,56,95,065	91,92,72,404
Investments- from earmarked & endowment funds	9	52,68,61,268	46,36,38,678
Investments-Others	10	1,00,00,000	1,00,46,575
Current Assets, Loans & Advances	11	11,73,49,744	13,10,91,338
TOTAL		**158,99,06,077**	**152,40,48,995**

As per our report of even date
for M/s G. R. Venkatanarayana
Chartered Accountants
FRN 004616S

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

Sd/-
(Ravi Subrahmanyan)
Director

Sd/-
(G. R. Venkatanarayana)
Partner
M No. 018067

BANGALORE / July 3, 2017

RAMAN RESEARCH INSTITUTE, BANGALORE
INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR ENDED 31ST MARCH 2017

(Amount in INR)

INCOME	Schedule	Current Year	Previous Year
Income from Sales/Services	12	-	-
Grants/Subsidies	13	32,97,33,000	28,35,45,000
Fee/Subscriptions	14	-	-
Income from Investments for earmarked/endowment funds)	15	-	-
Income from Royalty	16	-	-
Interest Earned	17	32,84,372	26,55,199
Other Income	18	14,99,441	13,90,541
Increase/Decrease in stock of finished goods	19	-	-
TOTAL (A)		**33,45,16,813**	**28,75,90,740**
EXPENDITURE			
Establishment Expenses	20	22,85,74,400	20,54,97,570
Other Administrative Expenses	21	11,90,50,629	10,52,30,559
Expendtiture on Grants/Subsidies	22	-	-
Interest	23	-	-
Depreciation (Net as per Schedule 8)		5,86,22,280	5,58,51,498
TOTAL (B)		**40,62,47,309**	**36,65,79,627**
Balance being excess of expenditure over income (A-B)		(7,17,30,496)	(7,89,88,887)
Transfer to Capital Fund -Creation of Capital Assets		(5,86,22,280)	(5,58,51,498)
Transfer to Capital Fund -Grant Balance (Recurring Grant)		(1,31,08,216)	(2,31,37,389)
BALANCE BEING SURPLUS/(DEFICIT) CARRIED TO CORPUS/CAPITAL FUND		**(7,17,30,496)**	**(7,89,88,887)**
Significant Accounting Policies	24		
Contingent Liabilities and Notes on Accounts	25		

As per our report of even date
for M/s G. R. Venkatanarayana
Chartered Accountants
FRN 004616S

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

Sd
(Ravi Subrahmanyan
Directo

Sd/-
(G. R. Venkatanarayana)
Partner
M No. 018067

BANGALORE / July 3, 2017

RAMAN RESEARCH INSTITUTE, BANGALORE
RECEIPTS AND PAYMENTS STATEMENT FOR THE YEAR ENDED 31ST MARCH 2017

(Amount in INR)

RECEIPTS	Current Year	Previous Year	PAYMENTS	Current Year	Previous Year
I. Opening Balances			**I. Expenses**		
a) Cash in hand	2,092	-	a) Establishment Exp	19,41,66,244	17,51,74,919
b) Bank Balances	1,47,28,657	76,48,639	b) Admin Expenses	3,43,46,275	3,77,76,101
c) Deposits	1,00,46,575	-			
d) Stamps (Franking M/C)	25,226	19,093	**II. Payments made against projects**	9,73,758	10,02,322
			III. Investments made		
II. Grants Received			a) Out of Earmarked/End. Funds	-	-
a) From Govt. of India	40,39,00,000	35,27,00,000	b) Out of own funds	-	-
b) From State Govt.	-	-			
c) From other sources	-	-	**IV. Increase in Current Assets**	1,56,02,263	14,63,50,731
			V. Capital Expenditure		
III. Project Receipts	65,15,764	-	a) Purchase of fixed assets	7,51,76,626	4,66,59,592
V. Increase in Current Liabilities	10,48,40,781	8,82,45,647	b) Expenditure on Work-in-progress	-	-
VI. Decrease in Current Assets	1,45,63,151	14,15,17,670	**VI. Refund of surplus money/Loans**		
VII. Interest Received			a) To the Govt. of India	-	-
a) On Bank deposits	34,21,574	27,04,444	b) To the State Govt.	-	-
b) on Loans, Advances etc.	6,863	3,65,585	c) To other providers of funds	-	-
VIII. Other Income (Specify)	5,20,521	3,42,851	**VII. Finance Charges (Interest)**		
IX. Amount Borrowed	-	-	**VIII. Decrease in Current Liabilities**	22,29,95,787	16,17,77,714
X. Any other receipts	-	-	**IX. Closing Balances:**		
			a) Cash in hand	-	2,092
			b) Bank Balances	53,08,669	1,47,28,657
			c) Deposits	1,00,00,000	1,00,46,575
			d) Stamps (Franking M/C)	1,582	25,226
TOTAL	**55,85,71,204**	**59,35,43,929**		**55,85,71,204**	**59,35,43,929**

-

As per our report of even date
for M/s G. R. Venkatanarayana
Chartered Accountants
FRN 004616S

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

Sd/-
(Ravi Subrahmanyan)
Director

Sd/-
(G. R. Venkatanarayana)
Partner
M No. 018067

BANGALORE / July 3, 2017

RAMAN RESEARCH INSTITUTE, BANGALORE

SCHEDULES FORMING PART OF BALANCE SHEET AS AT 31ST MARCH 2017

(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	103,08,66,224		104,69,54,686	
Addition during the year	13,52,20,272		9,20,27,215	
Less: Deductions during the year *(includes WIP/Advances capitalised)*	6,01,75,331		5,22,64,179	
Less: Depreciation chargeable	5,86,22,280		5,58,51,498	
BALANCE AS AT THE YEAR END		104,72,88,885		103,08,66,224
(2) GRANT BALANCES				
(a) NON-RECURRING GRANT				
Balance as at the beginning of the year		1,16,88,932		(1,83,43,497)
Add: Contributions during the year	7,41,67,000		6,91,55,000	
Add: Interest earned on LC Margin Money & Term Deposits	8,20,118	7,49,87,118	6,40,465	6,97,95,465
Less: Expenditure incurred during the year		7,50,44,941		3,97,63,036
(Nett Addition-As per Schedule 8)				
BALANCE AS AT THE YEAR END		1,16,31,109		1,16,88,932
(b) RECURRING GRANT				
Balance as at the beginning of the year	(2,61,00,006)		(29,62,617)	
Transferred from Income & Expenditure-	(1,31,08,216)		(2,31,37,389)	
-Account for the year				
BALANCE AS AT THE YEAR END		(3,92,08,222)		(2,61,00,006)
TOTAL (1+2)		**101,97,11,772**		**101,64,55,150**

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

RAMAN RESEARCH INSTITUTE, BANGALORE
SCHEDULES FORMING PART OF BALANCE SHEET AS AT 31ST MARCH 2017

Schedule 3- Earmarked/Endowment Funds

(Amount in INR)

Sl No	Project Name	Funding Agency	Opening Balance	Additions during the year	Utilisation			Total Utilisation	Balance as on 31/03/17
					Capital Expenditure	Recurring Expenditure	Advances/ Receivables		
Funded by Government Agencies									
1	ISRO-Polix Project-Prof Biswajit	ISRO	43,38,039	-	-	1,49,047	-	1,49,047	41,88,992
2	DST-MWA Project- Prof Shiv Sethi	DST	36,269	-	-	-	-	-	36,269
3	Ramanujan Fellowship- Dr Pramod	DST	2,06,447	-	-	-	-	-	2,06,447
4	Indo-Aus BMWF Jt. Research	DST	70,579	-	-	-	-	-	70,579
5	Biomechanics of Synaptogesis-Dr Pramod	DBT	7,321	-	-	-	-	-	7,321
6	Dr. Bhatnagar Award-Prof. Madan Rao	CSIR	(7,20,000)	5,40,000	-	-	-	-	(1,80,000)
7	Indo-Aus Strategic Res. Fund- Dr Reji	DST	(4,820)	-	-	-	-	-	(4,820)
8	CEFIPRA Grant- Prof Hema R	IFCPAR	1,37,525	-	-	-	-	-	1,37,525
9	Sr. Research Fellowship-Karthik Sarkar	CSIR	(38,524)	38,524	-	-	-	-	-
10	Indo-Russia Joint Project- Prof Biman Nath	DST	4,73,600	-	-	-	-	-	4,73,600
11	Ramalingaswamy Fellowship- Dr. Gautam	DBT	1,97,834	14,12,000	-	18,74,797	-	18,74,797	(2,64,963)
12	Dr. Bhatnagar Award-Dr. Sadiq Rangwala	CSIR	-	1,80,000	-	1,80,000	-	1,80,000	-
13	Inspire Fellowship-Dr. Saurav Datta	SERB	9,36,251	8,71,928	-	18,89,982	-	18,89,982	(81,803)
14	CEFIPRA Grant- Dr. Sadiq Rangwala	IFCPAR	7,61,600	35,00,000	-	-	-	-	42,61,600
15	Dr. Bhatnagar Award-Prof Deshpande	CSIR	-	1,80,000	-	1,80,000	-	1,80,000	-
16	Inspire Fellowship-Dr. Dibyendu	SERB	13,59,533	3,00,000	-	17,69,799	-	17,69,799	(1,10,266)
	TOTAL		**77,61,654**	**70,22,452**	**-**	**60,43,625**	**-**	**60,43,625**	**87,40,481**
Funded by other than Government Agencies									
1	FQXi- Dr. Sumati Surya	FQXi	(15,922)	50,873	-	4,00,036	-	4,00,036	(3,65,085)
2	IAGRG Grant-Dr. Sumati Surya	IAGRG	902	-	-	-	-	-	902
3	CNRS-Dr. Urbasi Sinha	CNRS	-	71,836	-	1,74,838	-	1,74,838	(1,03,002)
	TOTAL		**(15,020)**	**1,22,709**	**-**	**5,74,874**	**-**	**5,74,874**	**(4,67,185)**
Retirement Funds									
1	Gratuity Fund	-	6,42,32,278	52,14,843	-	24,17,115	-	24,17,115	6,70,30,006
2	Leave Salary Fund	-	5,39,84,093	43,78,200	-	22,51,652	-	22,51,652	5,61,10,641
3	Pension Commutation Fund	-	18,48,17,530	1,50,72,911	-	13,58,925	-	13,58,925	19,85,31,516
4	RRI Pension Fund	-	6,34,71,244	2,54,66,508	-	-	-	-	8,89,37,752
5	RRI Provident Fund	-	11,67,63,468	1,55,06,549	-	-	5,49,837	5,49,837	13,17,20,180
	TOTAL		**48,32,68,613**	**6,56,39,011**	**-**	**60,27,692**	**5,49,837**	**65,77,529**	**54,23,30,095**
	GRAND TOTAL		**49,10,15,247**	**7,27,84,172**	**-**	**1,26,46,191**	**5,49,837**	**1,31,96,028**	**55,06,03,391**

RAMAN RESEARCH INSTITUTE, BANGALORE
SCHEDULES FORMING PART OF BALANCE SHEET AS AT 31ST MARCH 2017

(Amount in INR)

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

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

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

Schedule-7- Current Liabilities & Provisions	Current Year		Previous Year	
A. CURRENT LIABLITIES				
1. Sundry Creditors				
a) for goods	-		6,38,256	
b) Others	1,04,61,368	1,04,61,368	1,09,53,391	1,15,91,647
2. Earnest Money Deposit		39,10,035		8,91,500
3. Statutory Liabilities				
a) Overdue				
b) Others	-		-	
4. Other Current Liabilities (Incl. Security Deposit)	17,87,391	17,87,391	11,58,948	11,58,948
TOTAL (A)		1,61,58,794		1,36,42,095
B. PROVISIONS				
1. Gratuity	88,224		88,224	
2. Superannuation / Pension	96,396		19,78,279	
3. Accumulated Leave Encashment	-		-	
4. Others (Specify)	32,47,500		8,70,000	
TOTAL (B)		34,32,120		29,36,503
TOTAL (A+B)		**1,95,90,914**		**1,65,78,598**

RAMAN RESEARCH INSTITUTE, BANGALORE
SCHEDULES FORMING PART OF BALANCE SHEET AS AT 31ST MARCH 2017

Schedule 8- Fixed Assets (Amount in INR)

Description	GROSS BLOCK					DEPRECIATION				NET BLOCK	
	Cost /Valuation as at the beginning of theyear	Additions During the year	Deductions during the year	Cost / Valuation at the end of the year	Rate	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	17,53,72,639	19,61,036	-	17,73,33,675	1.63	3,00,03,272	28,74,556	-	3,28,77,828	14,44,55,847	14,53,69,367
3. Canteen Infrastructure	42,76,021	92,250	-	43,68,271	4.75	12,18,666	2,07,493	-	14,26,159	29,42,112	30,57,355
4. Plant Machinery, Equipment	86,76,25,139	4,94,20,795	4,63,197	91,65,82,737	4.75	33,84,44,474	4,25,18,228	64,597	38,08,98,105	53,56,84,632	52,91,80,665
5. Vehicles	50,80,027	23,71,903	-	74,51,930	9.50	47,66,914	5,95,268	-	53,62,182	20,89,748	3,13,113
6. Furniture & Fixtures	1,42,19,441	7,18,810	-	1,49,38,251	6.33	81,74,483	9,34,531	-	91,09,014	58,29,237	60,44,958
8. Computer Peripherals	15,48,88,885	42,69,065	-	15,91,57,950	16.21	15,34,12,036	6,70,884	-	15,40,82,920	50,75,030	14,76,849
9. Library Books	22,85,66,406	8,05,350	-	22,93,71,756	4.75	11,11,33,727	1,08,85,917	-	12,20,19,644	10,73,52,112	11,74,32,679
Total Fixed Assets	**153,35,89,990**	**5,96,39,209**	**4,63,197**	**159,27,66,002**		**64,71,53,572**	**5,86,86,877**	**64,597**	**70,57,75,852**	**88,69,90,150**	**88,64,36,418**
B. Capital Work in Progress											
Building	-	-	-	-		-	-	-	-	-	-
Capital Equipment	3,28,35,986	7,55,81,063	5,97,12,134	4,87,04,915		-	-	-	-	4,87,04,915	3,28,35,986
Total Capital Work in Progress	**3,28,35,986**	**7,55,81,063**	**5,97,12,134**	**4,87,04,915**		**-**	**-**	**-**	**-**	**4,87,04,915**	**3,28,35,986**
Grand Total	**156,64,25,976**	**13,52,20,272**	**6,01,75,331**	**164,14,70,917**		**64,71,53,572**	**5,86,86,877**	**64,597**	**70,57,75,852**	**93,56,95,065**	**91,92,72,404**

RAMAN RESEARCH INSTITUTE, BANGALORE
SCHEDULES FORMING PART OF BALANCE SHEET AS AT 31ST MARCH 2017

(Amount in INR)

Schedule 9- Investments from Earmarked/Endowment Funds	Current Year	Previous Year
1. In Fixed Deposits		
RRI Pension Fund	8,38,58,227	5,42,41,228
RRI Provident Fund	12,13,30,878	10,63,63,549
2. Other Approved Securities	-	-
3. Shares	-	-
4. Debentures / Bonds	-	-
5. Subsidiaries and Joint Ventures	-	-
6. Retirement funds invested in SBI Life Insurance Limited	32,16,72,163	30,30,33,901
TOTAL	**52,68,61,268**	**46,36,38,678**

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	1,00,46,575
TOTAL	**1,00,00,000**	**1,00,46,575**

RAMAN RESEARCH INSTITUTE, BANGALORE

SCHEDULES FORMING PART OF BALANCE SHEET AS AT 31ST MARCH 2017

(Amount in INR)

Schedule 11- Current Assets, Loans & Advances	Current Year		Previous Year	
A. CURRENT ASSETS				
1. Inventories		13,43,893		14,61,442
2. Cash balances in hand (Including cash imprest)		-		2,092
3. Unused stamp value on Postal Franking Machine		1,582		25,226
4. Bank Balances				
Main Account				
On Current Accounts	11,88,426		1,40,15,603	
On Savings Bank Account	41,20,243	53,08,669	7,13,054	1,47,28,657
Pension Fund Account				
On Current Accounts	29,60,718		52,35,055	
On Savings Bank Account	1,74,535	31,35,253	29,14,559	81,49,614
Provident Fund Account				
On Current Accounts	69,50,247		47,57,979	
On Savings Bank Account	5,66,462	75,16,709	34,87,997	82,45,976
TOTAL (A)		1,73,06,106		3,26,13,007
B. LOANS/ADVANCES AND OTHER ASSETS				
1. Advances and other amounts recoverable in cash				
On Capital Account	8,89,61,800		8,89,61,800	
Deposits	39,80,106		33,21,706	
Others	16,23,736	9,45,65,642	29,04,011	9,51,87,517
2. Income Accrued				
Main Account	4,46,329		2,752	
Provident Fund Account	21,33,376		14,89,924	
Pension Fund Account	15,20,651	41,00,356	7,10,887	22,03,563
3. Claims Receivable				
Main Account	2,14,802		53,717	
Provident Fund Account	7,39,217		6,64,019	
Pension Fund Account	4,23,621	13,77,640	3,69,515	10,87,251
TOTAL (B)		10,00,43,638		9,84,78,331
TOTAL (A+B)		**11,73,49,744**		**13,10,91,338**

RAMAN RESEARCH INSTITUTE, BANGALORE

SCHEDULES FORMING PART OF INCOME & EXPENDITURE ACCOUNT FOR THE YEAR ENDED 31ST MARCH 2017

(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	10,00,000	50,00,000
i) Plan-Recurring	32,87,33,000	27,85,45,000
Total	**32,97,33,000**	**28,35,45,000**

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

Schedule 15- Income from Investments	Current Year	Previous Year
NOT APPLICABLE	-	-
Total	**-**	**-**

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

Schedule 17- Interest Earned	Current Year	Previous Year
1) On Term Deposits		
a) With scheduled banks	28,26,891	17,57,414
2) On Savings Accounts		
a) With Scheduled banks	2,20,894	3,09,317
3) On Loans/Advances		
a) Employees	2,36,587	5,88,468
Total	**32,84,372**	**26,55,199**

RAMAN RESEARCH INSTITUTE, BANGALORE

SCHEDULES FORMING PART OF INCOME & EXPENDITURE ACCOUNT FOR THE YEAR ENDED 31ST MARCH 2017

(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	14,99,441	13,90,541
Total	**14,99,441**	**13,90,541**

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

Schedule 20- Establishment Expenses	Current Year	Previous Year
a) Salaries & Wages	7,89,47,559	7,92,60,114
b) Allowances & Bonus	10,20,50,708	8,81,71,728
c) Contrbution to Provident Fund	14,00,118	15,72,292
d) Contribution to NPS	25,55,357	20,79,245
e) Staff welfare expenditure	85,42,354	93,22,456
f) Retirement/Terminal benefits	3,50,78,304	2,50,91,735
Total	**22,85,74,400**	**20,54,97,570**

Schedule 21- Other administrative expenses	Current Year	Previous Year
1) Advertisement	1,78,493	1,95,302
2) Amenities	21,11,512	15,03,341
3) Audit Fee	57,500	1,12,700
4) Bank Charges	21,344	18,938
5) Campus Maintenance	94,65,511	97,97,486
6) Conveyance	6,69,574	5,22,573
7) Corporation Taxes	2,99,766	2,18,659
8) Creche	1,05,000	2,40,000
9) Electricity Charges	1,19,93,127	1,16,63,088

Schedule 21- Other administrative expenses (Continued)	Current Year	Previous Year
10) Entertainment & Hospitality	1,07,581	3,48,603
11) Freight	3,01,771	3,22,880
12) Honorarium & Professional Fee	67,75,542	50,41,217
13) Inter Institutional Collaboration	2,38,378	1,50,000
14) Journal Subscription	32,24,174	55,44,222
15) Lease Rent (Gauribidanur Land)	4,06,348	3,81,176
16) Miscellaneous Expenses	8,03,991	8,25,201
17) Outreach	10,50,131	3,04,197
18) Patent Fee	7,38,675	16,42,823
19) Payroll Processing Charges	4,12,227	3,65,983
20) Ph.D Programme Expenditure	19,98,703	19,53,264
21) Postage & Courier Charges	1,94,512	1,52,948
22) Printing & Stationery	6,87,016	2,60,986
23) Project Working Expenses	9,59,500	14,30,529
24) Repairs & Maintenance	89,47,223	76,13,731
25) Security	80,09,658	75,58,788
26) Seminar/Conference/Summer School	26,32,392	33,00,798
27) Stores & Consumables	3,61,05,695	2,25,18,886
28) Telephone & Communication Charges	24,86,774	19,40,390
29) Travel Expenditure	75,83,098	75,71,722
30) Uniform & Livery	1,38,225	2,10,547
31) University Affiliation Fee	-	9,00,000
32) Vehicle Maintenance/Transport	26,72,030	22,98,658
33) Visiting Students Programme	45,51,033	63,96,952
34) Wages	14,32,800	8,77,400
35) Water Charges	16,91,325	10,46,571
Total	**11,90,50,629**	**10,52,30,559**

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

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

RAMAN RESEARCH INSTITUTE, BANGALORE

Schedule-24

SIGNIFICANT ACCOUNTING POLICIES

1. General

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

2. Fixed Assets

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

3. Depreciation

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

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

Depreciation is charged in the Income & Expenditure account. Full depreciation is charged on assets procured 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 Plan and Non-Plan is Accounted for as Core Grants.

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

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

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

6.	Foreign Currency Transactions	Transactions denominated in Foreign Currency are accounted for at the rates prevailing on the date of actual transaction. No provision is made to account for gains and losses arising out of exchange fluctuations.
7.	Retirement Benefits	The Institute's contribution to Provident Fund and Pension Fund are charged to Income & Expenditure Account. Deficit, if any, in the Provident Fund and Pension Account is being provided for in the books. There has been no deficit in Provident Fund Account this year

Schedule-25

CONTINGENT LIABILITIES AND NOTES ON ACCOUNTS

A. Contingent Liabilities

1.	Claims against the Institute not acknowledged as debt	The Institute has established a Letter of Credit favouring Toptica Photinics, Germany against Purchase Order No. F-119/Lamp/2016-17 through State Bank of India vide their LC No. 4069117IM000096. Supplies against this LC would conclude in FY 2017-18.
2.	Bank guarantees given by the Institute	NIL
3.	Disputed demands in respect of taxes	NIL

B. Notes on Accounts

1.	Current Assets, Advances & Deposits	Current Assets, Advances and Deposits have a value on realisation in the ordinary course of activities. The extent of realisation is equal atleast to the aggregate amount appearing in the Balance Sheet
2.	Employees' Retirement Benefits	a. Institute's contribution to the Provident Fund account are charged to Income & Expenditure Account of the institute b. As prescribed by the Govt. of India, the Institute has subscribed to Pension funds 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 conveyance deed is yet to be signed pending a formal approval from Government of India. It is to be noted that a part of this land is earmarked for Indian Academy of Sciences. The Academy has made a token remittance of Rs. 1,00,00,000/-. This is shown as part of Schedule 7 (A)-Sundry Creditors (for others) that forms part of the Balance Sheet. A matching current asset, in form of an investment, has been created in the books as shown in Schedule 10.

4. Schedules 1 to 25 are annexed to and form an integral part of the Balance Sheet as at 31st March 2017 and the Income & Expenditure Account for the year ended on that date.

5. Following the changeover in financial reporting as per Uniform Format of Accounts, numbers pertaining to the previous years have been regrouped and rearranged to conform to current year figures

As per our report of even date
For **G. R. Venkatnarayana**
Chartered Accountants
FRN 004616S

Sd/-

(C. S. R. Murthy)
Administrative Officer

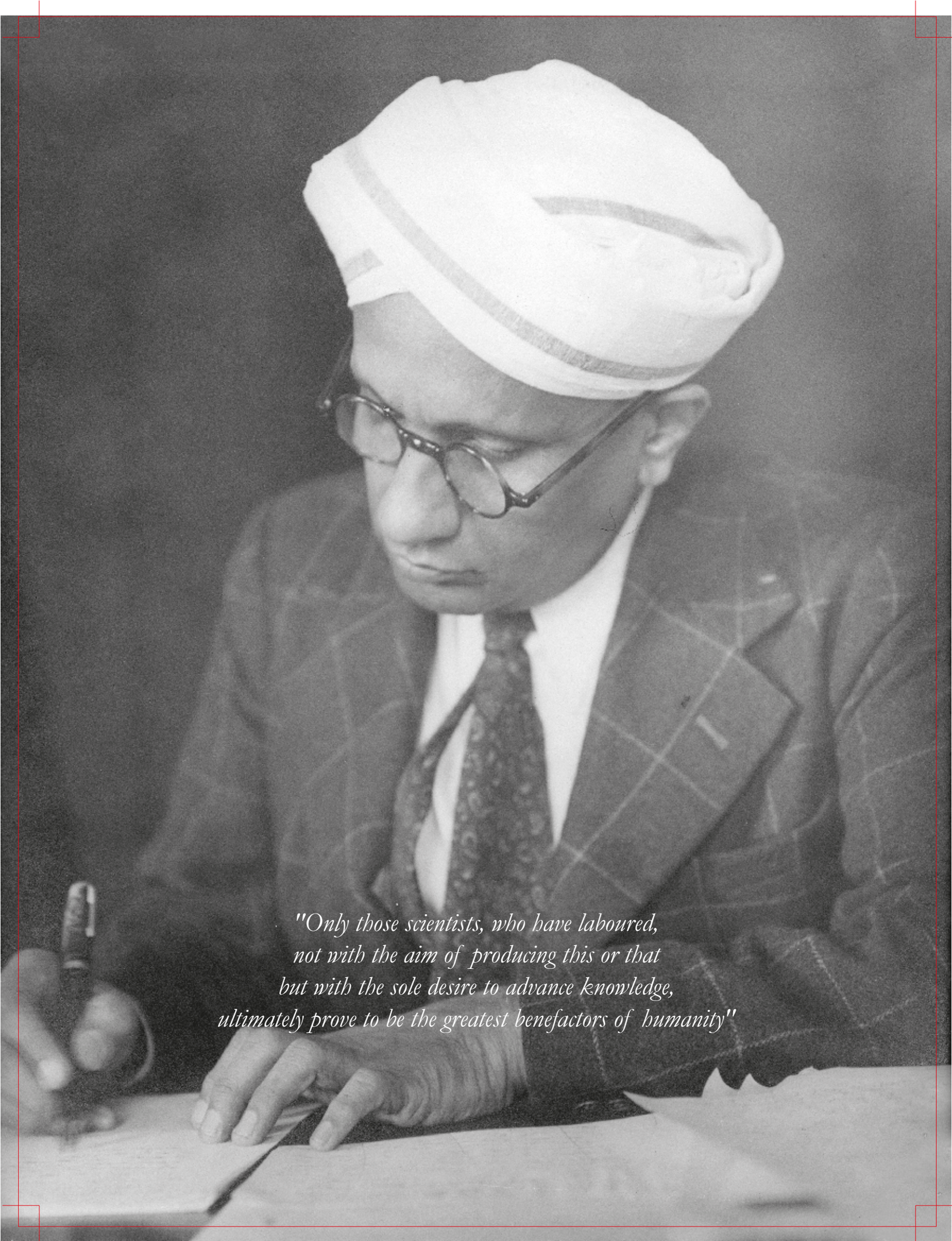
Sd/-

(Ravi Subrahmanyan)
Director

Sd/-

(G. R. Venkatnarayana)
Partner
M. No. 018067

BANGALORE / July 3, 2017



"Only those scientists, who have laboured,
not with the aim of producing this or that
but with the sole desire to advance knowledge,
ultimately prove to be the greatest benefactors of humanity"

Canteen

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