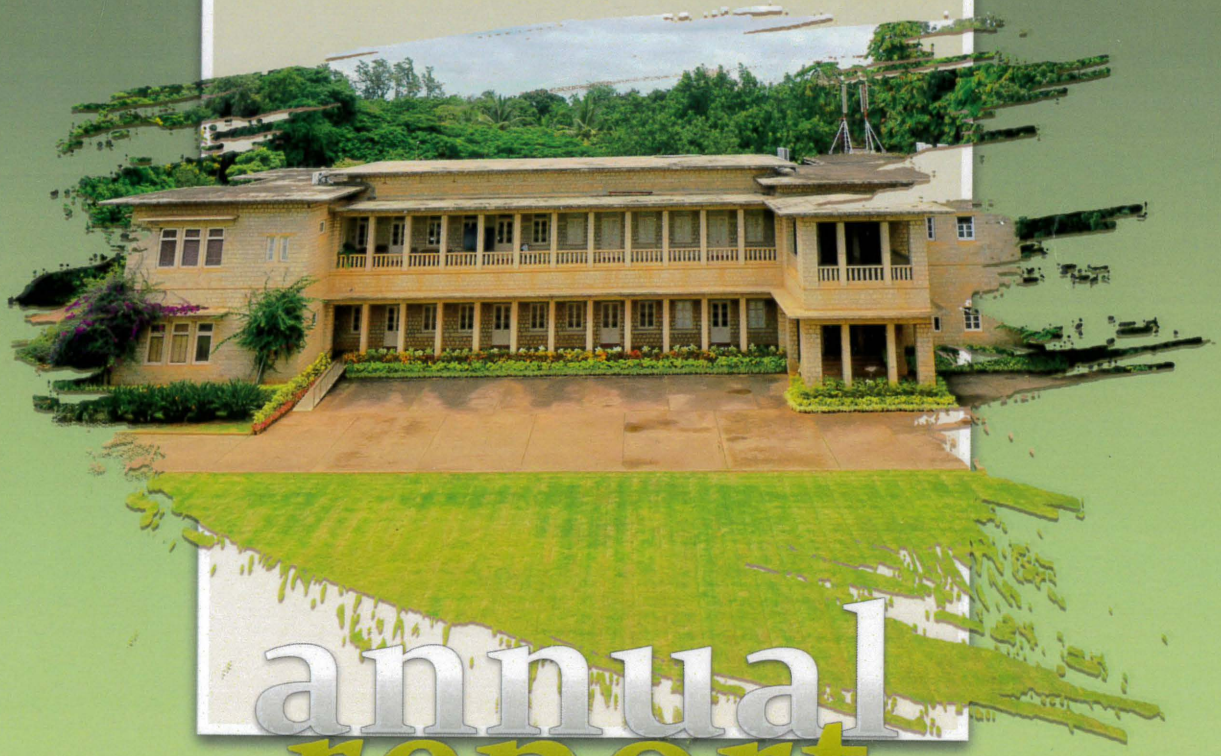
Raman Research Institute



annual report

2020-21

Raman Research Institute
Annual Report : 2020 - 2021

It is my earnest desire to bring into existence a centre of scientific research worthy of our ancient country where the keenest intellect of our land can probe into the mysteries of the Universe and by so doing help us to appreciate the transcendent Power that guides its activities. This aim can only be achieved if by His Divine Grace, all lovers of our country see their way to help the cause

C. V. Raman

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Raman Research Institute
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from the director

The Annual Report of the Raman Research Institute for the year 2020-21 is a synopsis of the research and academic activities at the Institute during the period 1st April 2020 to 31st March 2021. While providing an overall view of the Institute's organisation and facilities, the report's primary aim is to place on record the research published in scientific journals, PhD degrees awarded and other scientific activities such as seminars, colloquia and webinars held at the Institute.

A total of 90 students are enrolled in the Institute's PhD program. Nine of them received PhD degrees and six submitted their PhD theses over the past year. Over the same period 134 research papers were published in refereed journals, most of them known for their high impact factors. Other publications include 6 papers in conference proceedings, some book chapters and popular science articles.

It seems obligatory to note the disruptive impact of the ongoing pandemic on various activities which, for a scientific institute, includes the shift to the mostly online nature of many interactions, the drop in visits by scientists, and the sporadic shutdown of laboratories, canteen and guesthouse. On the other hand, many staff members went to great lengths to ensure smooth running of the administration and establishment and attending to medical emergencies. Others provided stimulus by organising online colloquia and journal clubs on a regular basis. Any attempt at list-making surely falls short, and I would like to record our deep gratitude to the many unacknowledged people whose efforts allow us to list our small-world concerns.

S Sridhar
6th August 2021

RRI at a glance

RRI is an Institute engaged in research in the basic sciences, founded by the Indian physicist and Physics Nobel Laureate Sir C V Raman, located in Bengaluru in a verdant 20-acre campus. The research is in various areas of physics spanning sub-atomic to cosmological length scales, overlapping with some areas of chemistry and biology. The scientists at RRI are organised in four groups, namely Astronomy and Astrophysics, Light and Matter Physics, Soft Condensed Matter Physics and Theoretical Physics; each group consists of faculty members, post-doctoral fellows, doctoral students, research assistants and visiting students, backed by administrative staff and a computer group. RRI is strongly invested in experimental research, which is supported by the laboratory of the electronics engineering group and the workshops of the mechanical engineering services.

History

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 founder's demise in 1970, a public charitable trust was created – the Raman Research Institute Trust – and the lands, buildings, deposits, securities, bank deposits, moneys, laboratories, instruments, and all other movable and immovable properties were transferred to the RRI Trust. The function of the RRI Trust was to maintain, conduct and sustain the Raman Research Institute.

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

Administration

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

Director

The current Director (i/c) of the Raman Research Institute is S Sridhar.

Research Laboratories

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

Research Facilities

Soft Matter Measurement Laboratories

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

Mechanical Engineering Services

- Mechanical Workshop
- Sheet metal, paint and carpentry facility

Electronics Engineering Group

Gauribidanur Field Station

Library

Computer Group

Infrastructure

- Guest House
- Canteen
- Clinic
- Sports facilities
- Crèche

Education

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

- PhD Programme
- Postdoctoral Fellowships
- Pancharatnam Fellowships
- Visiting Students Programme
- Research Assistant Programme

Funding

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

Council

Prof. Ajay K Sood (Chairperson)
Year of Science Chair Professor
Department of Physics
Indian Institute of Science
Bengaluru 560 012

Dr. K Kasturirangan
Honorable Distinguished Advisor
Indian Space Research Organisation, Bengaluru
Emeritus Professor, National Institute of Advanced Studies, Bengaluru
Chancellor, Central University of Rajasthan, Rajasthan
Chairman, National Steering Committee for National Curriculum Frameworks

Prof. Vijay P Bhatkar
Chancellor of Nalanda University
Chairman of ETH Research Lab
National President of Vijnan Bharati
Bavdhan, Off Mumbai-Bengaluru Bypass
Pune 411 021

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

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

Shri Vishvajit Sahay
Additional Secretary & Financial Adviser
Department of Science & Technology
Ministry of Science & Technology
Technology Bhavan, New Mehrauli Road
New Delhi 110 016

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

Prof. S Sridhar (Ex-Officio Member)
Director (i/c)
Raman Research Institute
C V Raman Avenue, Sadashivanagar
Bengaluru 560 080

Finance Committee

Prof. Ajay K Sood (Chairperson)
Year of Science Chair Professor
Department of Physics
Indian Institute of Science
Bengaluru 560 012

Shri Vishvajit Sahay
Additional Secretary & Financial Adviser
Department of Science & Technology
Ministry of Science & Technology
Technology Bhavan, New Mehrauli Road
New Delhi 110 016

Prof. H S Mani
Adjunct Professor
Chennai Mathematical Institute
H1, SIPCOT IT Park, Kelambakkam Siruseri
Tamil Nadu 603 103

Prof. S Sridhar (Ex-Officio-Member)
Director (i/c)
Raman Research Institute
Bengaluru 560 080

Academic Committee

Prof. S Sridhar (Chairperson)
Director (i/c)
Raman Research Institute
C V Raman Avenue, Sadashivanagar
Bengaluru 560 080

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

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

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

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

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

Prof. Sadiqali Rangwala
Light and Matter Physics Group
Raman Research Institute
C V Raman Avenue, Sadashivanagar
Bengaluru 560 080

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

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

organisation chart

Director

Ravi Subrahmanyan
(till 30.7.2020)

V A Raghunathan
(in-charge
1.8.2020 – 30.11.2020)

S Sridhar
(in-charge
1.12.2020 – 31.3.2021)

V G Subramanian
Scientific Officer

A&A
Nayantara Gupta
(till 22.3.2021)
Biman Nath
(from 24.3.2021)

TP
Dibyendu Roy
(till 19.3.2021)
Madhavan Varadarajan
(from 20.3.2021)

SCM
Ranjini Bandyopadhyay

LAMP
Andal Narayanan

Administration
V S Naresh

- **Accounts**
  Suresh Varadarajan
- **Purchase**
  C N Ramamurthy
- **Stores**
  B S Murthy
- **Establishment**
  Sachin S Belvadi

Library
B M Meera
(till 31.5.2020)

Computers
Jacob Rajan

MES
Mohammed Ibrahim

GBD Field Station
B Ramesh

EEG
A Raghunathan

RRI Science Forum	Gautam Soni, Andal Narayanan, Nayantara Gupta
Colloquia	Ranjini Bandyopadhyay (Chair), Urbasi Sinha, Vikram Rana, Dibyendu Roy (from 27.1.2021)
Hostel Wardens	Shiv Sethi, Arun Roy, B Ramesh, Urbasi Sinha
Admissions Coordinators	Sayantan Majumdar (Chair), Reji Philip (from 1.9.2020), Vikram Rana (till 31.8.2020)
Students Academic Affairs Committee	Sadiq Rangwala (Chair), Pramod Pullarkat, Shiv Sethi, Sumati Surya, Reji Philip
In-House meeting	PhD students – 3rd year
Joint Astronomy Programme Representative of RRI	B Ramesh
Complaints Committee	Srivani (Chair), V S Naresh, K N Vasudha, R Mamatha Bai, Bhanu Ravinder (External member)
Overseas Travel Committee	Biswajit Paul (Chair), Reji Philip, Supurna Sinha
Evaluation Committee	V A Raghunathan (Chair - till 14.12.2020), Sumati Surya, Biman Nath (Chair from 15.12.2020), Sadiq Rangwala, Ranjini Bandyopadhyay
Coordinators of Visiting Students Programme	V S Naresh
Library Committee	B M Meera (Chair till 31.5.2020), Supurna Sinha, Nayantara Gupta, Andal Narayanan, Ranjini Bandyopadhyay
RRI Official Language Implementation Committee	V S Naresh, Suresh Varadarajan, C N Ramamurthy, B Srinivasamurthy, B M Meera (till 31.5.2020), K Radhakrishna (till 31.5.2020), V Vidyamani, Harini Kumari, R Mamatha Bai, Jacob Rajan
Sports Committee	Sayantan Majumdar (Chair), Bapan Debnath, Sachin Belvadi, Sebanti Chattopadhyay, Nomaan X (till 28.2.2021)
Anti-ragging Committee	Director (Chair), Chandrashekar M R (External Member), Ranjini Bandyopadhyay, K S Srivani, Saumya Ranjan Behera, Palak
Research Facilities Committee	Biswajit Paul (Chair), Andal Narayanan, Pramod Pullarkat, A Raghunathan

RRI is an Institute engaged in research in the basic sciences, founded by the Indian physicist and Physics Nobel Laureate Sir C V Raman, located in Bengaluru in a verdant 20-acre campus. The research is in various areas of physics spanning sub-atomic to cosmological length scales, overlapping with some areas of chemistry and biology. The scientists at RRI are organised in four groups, namely Astronomy and Astrophysics, Light and Matter Physics, Soft Condensed Matter Physics and Theoretical Physics; each group consists of faculty members, post-doctoral fellows, doctoral students, research assistants and visiting students, backed by administrative staff and a computer group. RRI is strongly invested in experimental research, which is supported by the laboratory of the electronics engineering group and the workshops of the mechanical engineering services.

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 founder's demise in 1970, a public charitable trust was created - the Raman Research Institute Trust – and the lands, buildings, laboratories, instruments, and all other movable and immovable properties were transferred to the RRI Trust. The function of the RRI Trust was to maintain, conduct and sustain RRI.

Administrative set-up

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

Objectives of RRI

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

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

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

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

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

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

The research conducted at the Institute continually advances knowledge base via an improved understanding of the fundamental laws and 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 in the above-mentioned areas through its vibrant Post-doctoral, Doctoral, Research Assistantship and Visiting Student programs. The work quality and quantity is evidenced by documented research reports provided annually to the Department of Science & Technology, Government of India.

The work of the Institute is with three objectives:

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 behaviours. 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.

KNOWLEDGE COMMUNICATION

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

PROMOTING ACADEMIC TRADITIONS

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

Overview

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

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

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.

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

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

A concise description of some of the research activities in Astronomy and Astrophysics during 2020-21 follows. For a comprehensive and detailed description of the research, the reader is invited to visit page 36 of this Annual Report.

Focus 2020-21

Theoretical Astrophysics and Cosmology

The universe that we inhabit is vast beyond comprehension, complex, constantly expanding and is populated by myriad astronomical entities. The universe is populated by stars, galaxies, galaxy clusters, also objects emitting high-energy particles like Blazars and Gamma Ray Bursts. The space between stars, galaxies, galaxy clusters and the roughly spherical region that extends out from a galaxy is permeated by diffuse gas and dust. These are known as interstellar medium, intergalactic medium, intracluster medium and circumgalactic medium respectively. The Universe is thus a very vibrant place with constant interactions and various dynamic processes that shape their evolution and in turn the evolution of the universe as a whole. By studying these cosmic entities, their evolution and physical properties, astrophysicists, and on a much larger scale, cosmologists try to understand the evolution of the universe and its workings within the framework of the known laws of physics and chemistry. Analytical modelling and/or numerical simulations shed light on these processes and add to the knowledge of our understanding of the Universe.

Interstellar and circumgalactic Medium

During the year in report, Biman Nath and his students studied (*Ranita Jana et al 2020 ApJL 903 L9*) the implications of cosmic ray population in the Milky Way Circumgalactic medium, and put constraints from the observed diffuse gamma-ray background and synchrotron radiation. As a follow-up of previous work on cosmic ray acceleration in massive star clusters, Biman Nath along with his collaborator has shown analytically that a significant fraction of the observed diffuse gamma-ray background in our Galaxy is contributed by interactions of cosmic rays from star clusters with the medium in the immediate vicinity (*MNRAS: Letters, Volume 499, Issue 1, November 2020, Pages L1–L5*).

Galactic Structure and Stellar Dynamics

S Sridhar had recently analysed numerical simulations and proposed a theory of the Spiral Structure of Disc Galaxies (*S Sridhar 2019 ApJ, 884, 3*). In this theory a transient spiral density wave leaves behind "scars" in phase space at the Lindblad and co-rotation resonances, and the reduced dissipation in the scars enables the renewal of new spiral modes through growth from the underlying discrete noise due to a finite number of stars in the galaxy. Powerful "global" techniques, perhaps difficult for most researchers to grasp, were used in the demonstration. S Sridhar is working on an equivalent physically intuitive model in which spiral structure arises as a quasistanding-mode in a resonant cavity due to a self-sustaining cycle of nearly lossless reflections.

Dust particles are an important component of galaxies. The spectrum of a galaxy is distorted by dust and the properties of dust attenuation are crucial in order to determine the intrinsic spectrum of a galaxy. The dust content of a galaxy is corelated to its structure and stellar activity. Studies undertaken during the past year by Sonali Sachdeva and Biman Nath with approximately 16000 galaxies has revealed a well-

defined trend between the dust attenuation and central concentration parameters of these galaxies.

The molecular disk in galaxies was thought to be a single-component system settled close to the midplane in galaxies. However, recent sensitive observations indicate otherwise and points towards an additional component with much higher thickness than what earlier believed. To investigate the same, Narendranath Patra employed a hydrostatic equilibrium condition in galactic disk, and investigated the observational signatures of the existence of a two-component molecular disk and found that the spectral observations with high spatial and spectral resolution for a low-inclination system is ideal to infer the presence of a two-component molecular disk in a galaxy (*Patra, N N, 2020b, A&A, 638, A66*).

High Energy Astrophysics

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

Research during the past year by Nayantara Gupta and collaborators using multiwavelength data obtained from various telescopes has enabled them to study via analysis and modeling the temporal and spectral variability of

(i) a blazar that is gravitationally lensed by atleast two galaxies (*J. Abhir et al 2021 ApJ 915 26*)

(ii) a rare blazar with parsec scale jets that is in a black hole binary system (*https://doi.org/10.1051/0004-6361/202140708*) and

(iii) orphan gamma-ray flares from three gamma ray bright balzars (*Journal of High Energy Astrophysics, 2021, Vol.29, p31–39*).

Another multi wavelength study of a gamma-ray fast spectrum radio quasar revealed that it has two zones of emission which when fitted with a two zone leptonic model provided estimates for the maximum required power in the jets (*arXiv:2107.10555*)

Cosmology

In theoretical cosmology, research efforts were towards detecting neutral hydrogen at high redshifts and the study of redshifted HI emission from the epoch of reionization and probing alternative dark matter models using cosmological observables. EDGES result has opened the possibility of energy injection in the early universe. Shiv Sethi and his students explored this possibility (*Nirmalya Brahma et al JCAP12(2020)034*) by considering energy injection from the decay of a dark matter particle close to the era of recombination and showed that this is the only viable route to explain the EDGES result through a pre-recombination era energy injection. In another work, Anjan Sarkar and Shiv Sethi have developed a meaningful way to distinguish alternative dark matter models by using the redshift evolution of the observable effective optical depth from the Lyman data as a discriminator between dark matter models that differ from the CDM model on small scales (*arXiv:2101.09917*).

Observational cosmology research is focused on design and characterization of custom built telescopes to detect 21 cm line from neutral hydrogen and deriving cosmological inferences. During the past year, as part of the HERA collaboration Saurabh Singh's work on forming statistical estimates of the data to constrain the properties of the first stars and galaxies has resulted in one of the most sensitive upper limits on the 21-cm signal.

Observational Astronomy

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

Radio and Ultraviolet Astronomy

Using uGMRT data Shiv Sethi, K S Dwarakanath and collaborators have measured HI emission from star-forming galaxies in the redshift range $0.7 < z < 1.35$. This is the first such detection of HI in emission at high redshifts (*Nature volume 586, pages369–372 (2020)*). Another study (*The Astrophysical Journal, 2021, Vol.914, p54*) of star forming complexes in the far-UV by K S Dwarakanath, Narendra Nath Patra and collaborators has enabled them to estimate the sizes, star formation rates, metallicities and the Toomre Q parameter of the star forming complexes.

X-ray Astronomy

Compact X-ray binaries are composed of a compact object, a white dwarf, neutron star or a black hole and a companion 'normal' star. The intense gravitation field of the neutron star causes matter from the companion star to accrete onto the neutron star, producing X-rays. X-ray astronomy is a powerful tool to study such objects. A plethora of information about system parameters like magnetic field geometry and strength, chemical composition of the surrounding medium and dynamics like orbital period and radius evolution of X-ray binaries, structural evolution of the accretion disk and its time scales, and structure in the stellar winds can be obtained by a careful analysis of the X-ray output from compact X-ray binaries. Specifically, in 2020-21 Biswajit Paul, his students and collaborators analysed (i) a Be X-ray binary (*MNRAS, 497,1,September 2020,1059–1065*) and provided inputs on the composition and magnetic field strength (ii) detected bursts from a low mass X-ray binary and characterized the

evolutionary stage, accretion disk geometry and coronal structure of the source (*New Astronomy, 2021, Vol. 83, 101479*).

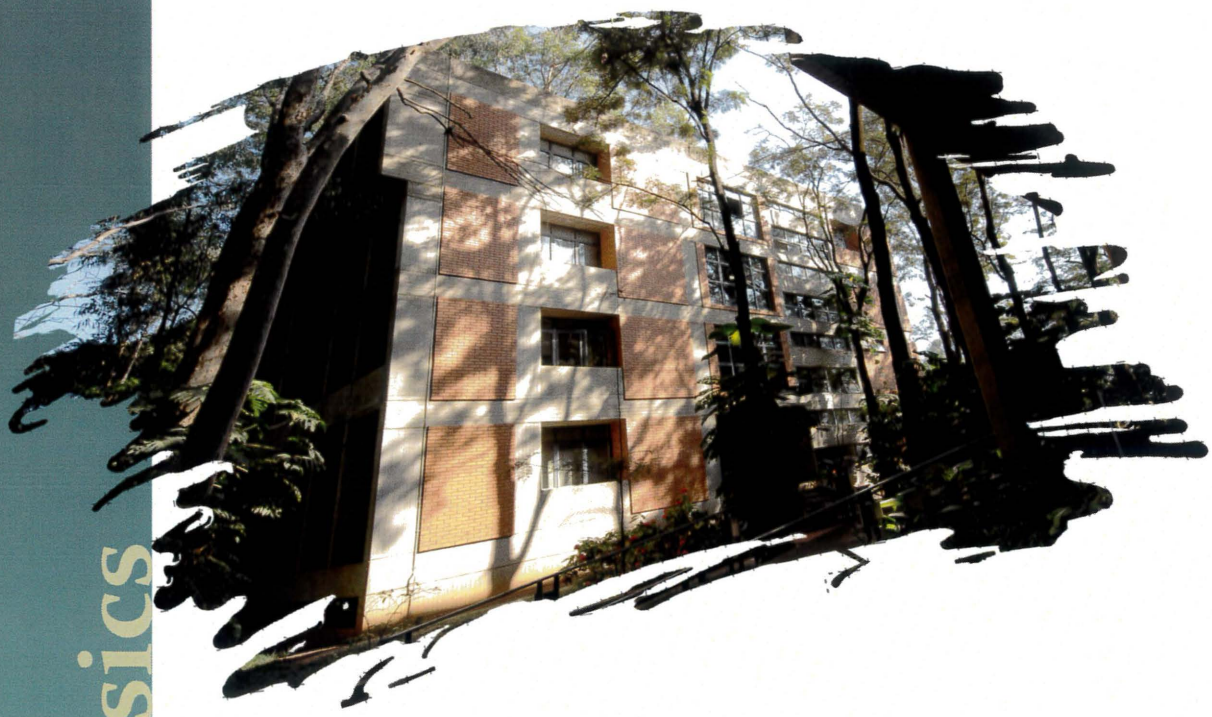
Research during the past year by Vikram Rana and his students was on understanding white dwarf-normal star binary system known as cataclysmic variables as well as timing and spectral analysis of ultraluminous X-ray sources.

Experimental Astronomy

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

Mayuri S Rao, Saurabh Singh, Jishnu Nambissan, Ravi Subrahmanyan, Udayashankar N, other members of the CMB distortions lab, Electronics Engineering Group (EEG), Mechanical Engineering Services (MES) at RRI and international collaborators are associated with different experiments terrestrially and in space that aim to detect the 21-cm signal from neutral hydrogen to understand the above periods of the evolution of Universe better. During the past year, progress has been made on developing and optimizing PRATUSH-C3, a precision spectral-radiometer as a payload on the Chadrayaan-3 mission. Focus has also been on enhancing the system detection capabilities of the next version of SARAS namely SARAS-4 system, another experiment aimed at detecting the global 21-cm signal. During 2020-21, the Qualification Model (QM) was completed and significant progress has been made towards completion of the Flight Model (FM) of POLIX, an Indian X-ray polarimeter to be launched as a payload on ISRO's satellite XPoSat. Biswajit Paul and many members of AA, EEG and MES have made major contributions in developing both the QM and FM. In another collaborative effort towards developing technology for a hard X-ray telescope, Vikram Rana conducted several tests on the inhouse built automated epoxy dispensing machine and fabricated mirror segments containing a single glass sheet and graphite spacers bonded with epoxy using this machine.

light & matter physics



Overview

Members of the light and matter physics (LAMP) group are engaged in research on fundamental properties of electromagnetic (EM) waves and on the nature of interaction of EM waves with gaseous neutral atoms, ions, ultra-cold and exotic states of matter. Scientists learn about the physical properties of objects ranging in size from that of the universe down to atomic scales by investigating the interaction of light with them. These investigations are aimed at revealing fundamental processes which will qualitatively improve our understanding of the studied phenomena and provide new guiding principles. The knowledge thus gained is of significant value both at the fundamental and at the applied realms. A concise description of some of LAMP group's research activities during the past year is given below. For a comprehensive and detailed description, the reader is invited to visit page 57 of this report.

Focus 2020-21

Ultracold Atoms, Molecules and Ions Research

Cooling and trapping of atoms, ions and molecules is one major area of research in the LAMP group, with the goal of studying interactions between them and also with electromagnetic fields at low temperatures. Sadiq Rangwala and group members have modeled ultracold lithium ion-atom collisions, and along with collaborator, aspects of interactions that play defining roles in the scattering calculations have been identified. They have also computed potential energy curves for $^{7}Li^{+}$-^{7}Li, $X^{2}\Sigma_{g}^{+}$ and $A^{2}\Sigma_{u}^{+}$, and determined their collisional properties. In another collaborative work, the collision rate coefficient for collisions between ultracold Cs atoms and low-energy Cs^{+} ions has been measured in a hybrid trap consisting of a magneto-optical trap (MOT) for Cs atoms and a Paul trap for Cs^{+} ions. Another investigation was regarding the performance of multipole, linear Paul traps in the study of cold ion–atom collisions, using a combination of numerical simulations and analysis based on the virial theorem.

Saptarishi Chaudhuri, Sanjukta Roy along with students have completed the installation of an ultra-high vacuum system for carrying out state-of-the-art Quantum Mixture experiment. The experiment has the long-term goal of investigating the emerging physics of quantum degenerate mixtures and polar molecules with tunable, long-range dipolar interactions to simulate complex condensed matter phenomena. In another set of experiments along with theory collaborators, the response function of cold atoms in a MOT subjected to a sudden mechanical impulse has been studied.

Precision Atom-Light Interaction and Spectroscopy

In the Quantum Optics lab, Andal Narayanan, students and collaborator have investigated an atom-light interaction scheme which creates strong superposition of internal states of atoms (called the dark state), using microwaves and optical fields. In this scheme which involves a nonlinear three-wave mixing process, the transmission and absorption properties of the optical probe field can be controlled using the phase of the microwave field, realizing a fast, high-contrast optical switch. The optical probe field is found to be amplified because of an interference between the microwave field and the coupling optical field, mediated by the dark state. In a related theoretical study by Andal, students and collaborators it was shown that by varying the phase and intensity parameters of a control microwave field, and employing the phenomenon of electromagentically induced transparency (EIT), the group delay of an optical pulse can be manipulated such that its speed can be varied from the subluminal (slow) to the superluminal (fast). In another study, Andal and students demonstrated the practical implementation of two digital phase modulation schemes connecting microwave and optical frequencies using an atomic radio-over-fibre device, in which a microwave carrier was modulated in the audio frequency range, and the signal was read out in the optical frequency range.

Saptarishi Chaudhuri, Sajukta Roy, and Dibyendu Roy along with students, have measured spin correlations and intrinsic spin relaxation lifetime in an ensemble of cold atoms using the Faraday rotation fluctuation technique. The measurements are carried out in cold ^{85}Rb atoms coherently driven by a pair of Raman laser beams, cooled down to the low temperature of 150 micro-Kelvin. This technique can be potentially used for the measurement of quantum correlations. A comprehensive theoretical description of the result has been developed based on Optical Bloch Equations (OBE). Another interesting result is the observation of inter-species spin-exchange collisions, measured in a thermal atomic vapor at room temperature. Here, resonant spin excitation in ^{85}Rb could be read via spin correlation spectroscopy in ^{87}Rb. This is one of the first direct detections of spin exchange collisions in atomic systems, where resonant spin exchange has transferred spin excitation from one species to another. In another study, neutral Rubidium atoms have been trapped and cooled in a micron sized MOT and high-resolution optical spectroscopy of Rydberg atoms has been undertaken by Saptarishi Chaudhuri, Sanjukta Roy and students. As low as 30 atoms could be trapped and cooled with a high lifetime of several tens of seconds. High resolution spectroscopy using EIT in ladder system is being performed to measure absolute transition frequencies of high fine structure states.

Intense Light-Matter Interactions

In the Ultrafast and Nonlinear Optics lab, Reji Philip, students and collaborators have carried out nonlinear absorption measurements in various materials including nitrochalcone derivatives, silver-decorated graphene oxide nanohybrids and alloy-nanoparticle embedded carbon nanotubes, yielding the effective two-photon absorption coefficients of these materials. Results indicate the potential of these materials for application as efficient optical limiters, for the safety of human eyes and sensitive optical detectors from accidental exposure to harmful laser radiation. In another collaborative study, surface structures have been fabricated on crystalline silicon by employing laser pulses of different widths. While ultrashort (100 fs) pulses lead to the formation of periodic and quasi-periodic nanoscale patterns, short (7 ns) pulses generate random microscale patterns on the surface. Silicon surfaces with periodic nanoscale patterns are useful for applications in photovoltaics, electro-optic devices and sensors. In another work, laser-produced plasma plumes have been generated from thin Ni films of 50 nm thickness coated on a quartz substrate in the relatively rare rear ablation geometry, under various ambient conditions. A detailed study of the acceleration of ions present in plasma plumes generated by nanosecond laser pulses has been performed for various laser energies and background gas pressures.

Quantum Communications, Quantum Optics and Quantum Information Science

At the QuIC lab, Urbasi Sinha and students and project staff are leading India's first satellite based quantum key distribution (QKD) project in collaboration with the Indian Space Research Organization. They are also working on integrated photonics based QKD in collaboration with Italian colleagues. The free space QKD in-lab experiment performed by the lab was chosen by the Department of Science and Technology as one of its top 20 innovations and also by India Science-The Nation's Science channel as one of its top 10 science achievements for the year 2020. A major part of the year has been spent in developing both physics as well as engineering based requirements for free space QKD through an atmospheric channel. The lab has conducted an end-to-end free space quantum key distribution in-lab experiment, and also performed an inter-building free space quantum communications experiment connecting two buildings at RRI through the atmosphere. This is the first such demonstration from India. A much needed simulation toolkit has been developed which is able to simulate end-to-end QKD protocol taking into account practical experimental imperfections. This development is called *qkdSim* and with QKD becoming commercially viable, it fills a very important gap between practical feasibility and ideal simulations. In other collaborative work, a novel QKD protocol using intra-particle entanglement, as opposed to the conventional inter-particle entanglement, has been developed. This promises higher key rates and lower quantum bit error rates than the inter particle counterpart.

In another work, a revolutionary new technique for quantum state estimation called *Quantum State Interferography (QSI)* has been devised and experimentally demonstrated. This is an alternative to the conventional quantum state tomography technique where the number of measurements required scales very unfavorably with dimensions. In QSI, the scaling with dimensions is linear as opposed to the usual quadratic scaling. Precise quantum state estimation is a necessary ingredient for various quantum technologies including quantum computing and quantum communications. This work was highlighted by the Department of Science and Technology as one if its top 20 innovations for 2020. Device independent random number generation through Hardy and Cabello Liang relations also has been performed.

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, polymer melts or solutions, paint and many biological materials like cells and tissue. 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. A concise description of some of SCM group's research activities during the past year is given below. For a comprehensive and detailed description, the reader is invited to visit page 74 of this report.

Focus 2020-21

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. 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. During 2020-21, Arun Roy and his students reported for the first time the formation of banded spherulite due to rhythmic growth of crystal-rich and crystal-poor zones in a pure liquid crystalline compound. Research was also towards synthesis and detailed experimental investigations of novel phase ordering and crystal polymorphism in liquid crystals (*RSC adv., 11, 4958 (2021)*).

Mechanical Properties of Soft Materials

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

Laponite is a colloidal synthetic clay that shows physical aging in aqueous suspensions due to the spontaneous evolution of inter-particle electrostatic interactions. Research during the past year by Ranjini Bandyopadhyay and her students (*Physics of Fluids 33, 013103 (2021)*) was on estimating the rates of destructuring of thixotropic suspensions via experimental studies and theoretical modelling of settling dynamics of falling spheres in laponite suspensions. Another study (*arXiv:2009.12741*) on the aging dynamics and rheology of laponite suspensions has revealed that solvent structure plays a key role in determining the dynamics and rheology of these suspensions. Research was also towards suppressing interfacial instability between

Newtonian and shear thinning viscoelastic fluids as a function of viscosity ratios of the two fluids (*arXiv:2010.10423*).

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

Research during the past year by Sayantan Majumdar and his students (*Soft Matter, 2021, 17, 6435*) has shed light on the yielding dynamics of networks formed by collagen (Type-I), the most abundant extracellular-matrix protein in mammals and the main structural and load-bearing element of connective tissues. This study can have potential applications in tissue engineering and designing resilient biological scaffolds. Another research focus was towards understanding the role played by actin filament alignment on mechanical hysteresis in cross linked biopolymers (*Soft Matter, 2021, 17, 5499*). Such studies can help in understanding how cells in our body dynamically control their material properties through remodeling of the cytoskeleton, an assembly of cross-linked filaments and bundles formed mainly by the biopolymer actin.

Biophysics

Nanoscale Biophysics of Biological Systems

Gautam Soni's Nano-Biophysics lab's research interests are primarily guided by the role of force in biophysical structure formation and its synergy with functional dynamics. They try to understand mechanisms of force sensing as well as force response of cells and molecules. They study this in biological model systems of protein assembly, DNA-protein complexes as well as whole cell mechano-sensing. They use, as well as develop, novel bio-nano and micro scale tools to decipher biophysical principles governing role of forces in cellular as well as molecular assemblies. During the past year, Gautam Soni, his students and collaborators demonstrated sensing (*Nanoscale (2021), 13, 320- 331*) using inhouse built quartz nanopores as a potential platform for an in-depth understanding of the structural landscapes of supercoiled DNA to decipher its functional role in different biological processes. Also, research efforts during the past few years culminated in the development of a high-resolution device for quantitative electrofluidic measurements and the reporting (*ACS Sensors (2020), 5(12): 3892–3901*) of first direct quantification of temporal and concentration-dependent changes in red blood cell volume upon ethanol exposure.

Biophysics of Axons

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

The extreme lengths to which axons grow poses several challenges to the neuronal cells. The maintenance of these structures and their function require constant back and forth transport of material like neurotransmitters, and material that need to be constantly recycled. Since diffusion is too slow for this (it will take >100 years for small molecules to diffuse a distance of 1 m), axons rely on molecular motors which can travel at speeds of up to micro-meters per second. Axons also face mechanical challenges as they are subjected to fast stretching during body movements—strain of up to 20% at some joints of mammals. The brain too, being one of the softest of tissues, undergoes shear deformations of the order of 5% in humans during normal activities like jumping, and much more during sudden impacts, like in contact sports. Even in the absence of such external stresses, axons have to maintain a balance of different internal stresses. The plasma membrane, composed of a fluid lipid bilayer, is under tension. A membranous tube under tension is unstable to peristaltic modes via the Rayleigh-Plateau instability, and require additional elements to maintain a uniform tubular form. This is achieved by forming connections with the internal cytoskeleton—an axisymmetric arrangement of different biopolymers and their associated proteins. This cytoskeleton highly dynamic as the polymers undergo turnover via constant polymerisation-depolymerisation processes and are acted upon by molecular motors which can generate active stresses on the filaments. Thus, the axon is a structure which is maintained under a dynamic steady state where the different membrane and cytoskeletal forces are balanced against each other. Any changes in this dynamic balance can lead to abnormalities in the axonal form and function. This is particularly significant for neuronal cells as they do not divide unlike other cells in a human body and are rarely replenished when lost. This makes the nervous system particularly susceptible to degeneration causing debilitating conditions. Axons, owing to their extreme lengths, are particularly vulnerable.

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

Research during the past year has been on studying the nonlinear mechanical response of axons when subjected to cyclic strains of varying magnitude and buckling of axons when released from a stretched state. This has enabled improvements to existing theoretical models

and a better understanding of viscoelastic response of microtubules. Laser cutting axons to investigate their behaviour is another area of active research.Apart from providing mechanistic insights into force balance between cytoskeletal components, these studies will also help us understand axon degeneration process after injury. Additionally, a fully automated microfluidic device has been developed inhouse for studying axonal membrane dynamics.

Physics of Lipid Membranes and Polyelectrolytes

V A Raghunathan's group is involved in investigations on the structure of soft materials and their phase behaviour, using small-angle and wide-angle X-ray scattering techniques. Systems studied include lipid-sterol membranes, lipid-polyelectrolyte complexes and surfactant solutions. The phase behaviour of these systems is also probed using optical and atomic force microscopy. In addition, the mechanical properties of lipid membranes are studied using optical microscopy and micropipette aspiration. During the past year, results from studies on zwitterionic lipids have shown that acidic pH plays a major role in the phase behaviour of these lipids.

theoretical physics

Overview

Theoretical physics is an endeavour that attempts to make sense of the inner workings of nature, using the language of mathematics. The goal is to model and predict the behaviour of all systems from the very small (sub-atomic and smaller) to the very large (galaxies and beyond) that constitute this beautiful and complex universe that we live in. The Theoretical Physics (TP) group at RRI is actively pursuing research in the following areas: Statistical Physics and Condensed Matter, Quantum Optics, Quantum Gravity, Foundations of Quantum Mechanics and General Relativity. TP group has also forged a robust collaboration with experimental groups within RRI. The connection with Light and Matter Physics group is specifically in the areas of foundational questions in quantum mechanics, quantum information, sensing and metrology and nonequilibrium quantum dynamics. The overlap with the Soft Condensed Matter group is in areas such as biophysics, polymer physics and modelling stochastic search process. Additionally, RRI theorists have fruitful ongoing collaborations in the above research areas with both national and international peers. A concise description of some of TP group's research activities undertaken during the past year is given below. For a comprehensive and detailed description the reader is invited to visit page 86 of this report.

Focus 2020-21

Nonequilibrium Statistical Physics and Stochastic Processes

Nonequilibrium systems are ubiquitous; found across diverse disciplines, ranging from physics, chemistry, biological and environmental sciences to finance. A system coupled to a thermal environment relaxes towards an equilibrium state. For example, a hot cup of coffee or a glass of cold drinks left sitting in a room tries to attain thermal equilibrium by exchanging heat with the surrounding gas molecules. A system can be kept out of equilibrium for an arbitrarily long time by connecting to multiple environments. For example, a thermal conductor connected to two heat reservoirs with different temperatures researches a nonequilibrium stationary state where heat flows at a constant rate from the hot reservoir to the cold reservoir through the conductor. Unlike for a system at equilibrium, the probabilities of different configurations of a nonequilibrium system are not a priori given but are determined by the underlying stochastic dynamics. This is often a challenging task due to the lack of a general framework. The scope of nonequilibrium statistical physics extends far beyond thermal systems. In fact, a system can also be inherently nonequilibrium because of its dynamics. For example, an athermal system like a continually shaken box of marbles reaches a nonequilibrium stationary state where the velocity distribution is not Boltzmann. Another example of broad interest is the so-called active motion, found in living systems ranging from bacterial motility at the microscopic scale to the flocking of birds and fish schools at the macroscopic scale as well as in artificial systems including granular matter, self-catalytic swimmers, and nano-motors. Researchers at RRI are interested in various aspects of nonequilibrium systems and stochastic processes, focusing on fundamental understanding as well as practical applications.

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

Some bacteria, exhibit a unique kind of direction reversing active motion, whereby, in addition to a diffusive change of direction, the motion also completely reverses its direction intermittently. Recent work (*Phys. Rev. E 104, L012601 (2021)*) by Ion Santra, Urna Basu and Sanjib Sabhapandit has provided answers to: How far does such a microorganism typically disperse in a given time? How long does it take (first-passage time) to find a food source? Another study (*J. Stat. Mech. 2020, 113206 (2020)*) by the same members on the effects of stochastic resetting on run and tumble particles has shed light on marginal and positional distributions as well as first passage properties for these class of particles. Efforts by Urna Basu and students (*Phys. Rev. E 102, 052129 (2020)*)towards studying the position distribution of an active Brownian particle (ABP) under different stochastic resetting protocols has led to a better understanding of the dynamical response of the ABP when subject to these protocols. Investigations (*J. Stat. Mech. 2020, 083207 (2020)*)of driven run and tumble

particles also known as persistent Brownian motion has enabled Sanjib Sabhapandit and collaborators to shed light on the probability distribution of these particles. In another work (*Phys. Rev. Lett. 125, 200601 (2020)*) Sanjib Sabhapandit and collaborator explore the freezing transition in the barrier crossing rate of a diffusing particle and show that the freezing transition occurs when in the associated quantum problem, the gap between the ground state (bound) and the continuum of scattering states vanishes.

Optimal Control in Pandemics

During a pandemic, there are conflicting demands arising from public health and socio-economic cost. Lockdowns are a common way of containing infections, but they adversely affect the economy. Joseph Samuel and Supurna Sinha studied (*Phys. Rev. E 103, L010301*) the question of how to minimize the socio-economic damage of a lockdown. They optimize the socio-economic cost for a fixed health cost and arrive at a strategy for navigating the pandemic.

Classical and Quantum Gravity

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

Loop Quantum Gravity

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

During the past year, Madhavan Varadarajan and collaborator re-examined gravitational evolution in terms of the classical variables underlying LQG and showed that time evolution of the classical gravitational field can be re-expressed as (a gauge covariant generalization of) the Lie derivative along a novel shift vector field in spatial directions. In another collaborative effort, Madhavan Varadarajan has disproved a long held belief that traditional LQG methods cannot yield a dynamics for quantum gravity which propagates quantum propagations.

Causal Set Theory

Causal Set Theory (CST) is a manifestly covariant approach to quantum gravity, which assumes that spacetime is fundamentally discrete. CST is motivated by deep theorems in Lorentzian geometry, and gives primacy to the causal ordering of spacetime events. In CST the causal structure (which is a partially ordered set) is quantised. It posits that the continuum is an approximation to an ensemble of underlying locally finite partially ordered sets or causal sets. During 2020-21, Sumati Surya and collaborator found (Class. Quantum Grav. 37 195030 (2020)) a criterion for extension (and thence covariance) in complex sequential growth models for causal sets. They have found a large family of models in which the measure extends, so that all covariant events/observables are measurable. In another work, (*Class. Quantum Grav. 38 045017(2021)*) Sumati Surya, Abhishek Mathur and Anup Anand Singh have extended the work of Loomis and Carlip on the contribution of sub-dominant bilayer orders to the causal set path-sum and showed that the link action suppresses the dominant Kleitman-Rothschild orders for the same range of parameters.

Nonequilibrium Quantum Dynamics

Equilibrium quantum dynamics has been investigated for almost a century now, and there are well-developed statistical mechanics descriptions both for closed (isolated/conservative) and open (coupled to bath/environment) quantum systems. There have also been tremendous efforts to generalize the above descriptions to out-of-equilibrium quantum systems. Yet, our current understanding of nonequilibrium quantum dynamics is still insufficient even after fifty years of intensive research. It is part of active research in recent years to know when and how a far-from-equilibrium closed quantum system relaxes to equilibrium. A system can be driven far-of-equilibrium by applying a mechanical (time-independent or -dependent electric or magnetic fields) perturbation or by keeping the system's boundaries in relative motion (shear) or maintained at different temperatures. When an out-of-equilibrium system does not relax to equilibrium, it generates two nonequilibrium systems: mechanical nonequilibrium systems and thermal nonequilibrium systems. Research along this direction at RRI broadly focuses on understanding nonequilibrium quantum dynamics in solid-state and atomic, molecular & optical (AMO) systems.

The pattern in particles' motion can be regular for exactly-solvable systems, e.g., a simple pendulum, and irregular or chaotic for complex systems, e.g., weather or superconducting junctions. Dibyendu Roy and collaborator identified (*Phys. Rev. E, 2020, Vol.102, Art. No. 060202(R)*) a new mechanism of chaos in a quantum system of a periodically kicked lattice of particles (e.g., electrons) in the presence or absence of a conserved particle number. Their

study sheds light on the spectral form factor (SFF), an important measure of chaotic behavior in such systems.

Specific quantum systems possess a band-structure topology, which gives rise to robust phenomena like the quantum Hall effect. In a recent work (*Phys. Rev. B, 2021, Vol.103, Art. No. 075441*), Dibyendu Roy and Vivek Vyas studied the topological aspects of periodically driven non-hermetian Su-Schrieffer-Heeger model and found that environmental interactions can lead to a strange underlying topology, which is also controllable. In another work (*arXiv:2010:08336*), Dibyendu Roy and collaborator used a generalization of the quantum Langevin equation and Green's function method to develop a unified description of electrical, thermal, and spin transport in open quantum systems made of topological superconductors, semiconductors, and metals.

During the past year, Suraka Bhattacharjee and Supurna Sinha used the Quantum Langevin equation as a starting point to study the response function, the position-velocity correlation function and the velocity autocorrelation function of a charged Quantum Brownian particle in a magnetic field coupled to a bath (*arXiv:2105.07036*). In another work, Supurna Sinha and collaborators provided theoretical analysis for an experimental effort by Saptarishi Chaudhuri from the Light and Matter Physics group towards measuring the response function of cold atoms in a 3D optical molasses (*arXiv:2101.09118*).

Closing Remarks

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

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

The Institute has a number of schemes that engenders creativity, higher learning and experimental skills in the next generation. In the last year, the scientific staff at RRI have mentored and educated around 150 students and young researchers, and provided opportunities for development of their potential towards being the scientists of tomorrow, by engaging with them in the Post-doctoral, PhD, Research Assistant, and Visiting Student Programmes.

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


research
knowledge creation

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:

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

Observational 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.

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

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

Focus 2020-21

Theoretical Astrophysics and Cosmology

The universe that we inhabit is vast beyond comprehension, complex, constantly expanding and is populated by myriad astronomical entities. The universe is populated by stars, galaxies, galaxy clusters, high energy objects like blazars and more. The space between stars, galaxies, galaxy clusters and the roughly spherical region that extends out from a galaxy is permeated by diffuse gas and dust. These are known as interstellar medium, intergalactic medium, intracluster medium and circumgalactic medium respectively. The Universe is a very vibrant place with constant interactions and various dynamic processes that shape their evolution and in turn the evolution of the universe as a whole. By studying these cosmic entities, their interactions and processes Astrophysicists, and on a much larger scale, Cosmologists try to understand the evolution of the universe and its workings within the framework of the known laws of physics and chemistry. Analytical modelling and/or numerical simulations shed light on these processes and add to the knowledge base of our understanding of the Universe. A detailed description of the research focus in Theoretical Astrophysics and Cosmology undertaken at the Institute during 2020-21 follows.

Interstellar and Circumgalactic Medium

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

With collaborators Eugene Vasiliev and Yuri Shchekinov, Biman Nath has been studying the CII emission lines from high redshift quasars to determine whether they are excited by stellar or AGN radiation. They used photoionization codes to shine high energy emission from the black hole and stellar radiation on the interstellar medium and showed that the observed ratio of CII line emission to far infrared radiation can be explained only with the help of obscured AGNs.

[Biman Nath and collaborators Eugene O Vasiliev (Southern Federal University, Russia) and Yuri A Shchekinov (Lebedev Physical Institute of Russian Academy of Sciences, Russia)]

Constraints on cosmic rays in the Milky Way circumgalactic medium

Biman Nath and his students Ranita Jana and Manami Roy studied the implications of cosmic ray population in the Milky Way Circumgalactic medium, and put constraints from the observed diffuse gamma-ray background and synchrotron radiation. This work is now published: *Ranita Jana et al 2020 ApJL 903 L9.*

[Ranita Jana, Manami Roy and Biman Nath]

Diffuse gamma-rays from star clusters

As a follow-up of previous work on cosmic ray acceleration in massive star clusters, Biman Nath and collaborator David Eichler have shown analytically that a significant fraction of the observed diffuse gamma-ray background in our Galaxy is contributed by interactions of cosmic rays from star clusters with the medium in the immediate vicinity. This work is now published: *MNRAS: Letters, Volume 499, Issue 1, November 2020, Pages L1–L5*

[Biman Nath and David Eichler (Ben Gurion University, Israel)]

Precipitation limited hot-haloes from massive galaxies to clusters

Biman Nath and collaborators Priyanka Singh and G M Voit investigated the precipitation model for circumgalactic medium, applied to hot haloes ranging from massive galaxies to galaxy clusters, in light of X-ray and Sunyaev-Zeldovich effect observations. They have shown that a single model can indeed explain the

observational trends, and have put constraints on the parameters based on MCMC calculations.

[Biman Nath and collaborators Priyanka Singh (INAF Italy and IFPU, Italy) and G M Voit (Michigan State University, USA)]

Galactic Structure and Stellar Dynamics

Spiral structure of disc galaxies

In a paper published in The Astrophysical Journal in 2019, S Sridhar constructed a model of a disc galaxy in which a transient spiral mode leaves behind "scars" in phase space at the Lindblad and co-rotation resonances. The distribution function (DF) of stars is "flattened" within resonant scars and undisturbed outside of them. Sridhar showed that this flattening results in drastic reduction of the dissipation of spiral modes that are subsequently generated from underlying discrete noise (due to a finite number of stars in the galaxy). Hence resonant scars enable the renewal of transient spiral modes, as studied in recent numerical simulations.

This demonstration used "global" techniques, exploiting the description of disc torques using the Lynden-Bell and Kalnajs (LBK) formalism. Whereas the technique is extremely powerful, it uses sophisticated methods with which a generic researcher in stellar dynamics is unlikely to be familiar. Therefore, Sridhar resolved to treat the problem using travelling waves in the "shearing sheet" formalism, invented by Goldreich & Lynden-Bell and Julian and Toomre in the 1960's. This is a beautifully intuitive method, treating spiral density waves as standing-modes in a resonant cavity. The aim is to calculate the reflection and absorption coefficients at the Lindblad and co-rotation resonances, and thereby prove that a quasi-standing-mode arises naturally through a self-sustaining cycle of reflections, with very little loss.

[S Sridhar]

Dust Attenuation Curves and Structure of Galaxies

Accounting for the effects of dust presence is crucial to trace the cosmic evolution of galaxies in an accurate manner. Other than being involved in molecular cloud cooling and star formation, dust present in the ISM of galaxies, reprocesses more than half of the stellar light. A dust attenuation curve of a galaxy represents the optical depth created by dust at each wavelength. Detailed information of this curve is crucial for accurate estimation of nearly all properties of a galaxy, especially its stellar mass and star formation rate.

The dust content of a galaxy has been found to be correlated with its geometry (or structure). However, this connection has not been explored in a systematic and quantitative manner. Identifying a structural indicator that is well correlated with dust, can help quantify the dust attenuation parameters for a large sample of galaxies with available structural parameters. The advantage being that structural parameters are much easier to compute from reasonable quality of optical data (for local as well as distant galaxies), as compared to the attenuation parameters which require multi-wavelength high-resolution spectral information and detailed modelling.

During the past year, Sonali Sachdeva and Biman Nath have taken a large sample of (~16000) galaxies to investigate the correlation of different structural indicators with dust attenuation parameters. All galaxies are from SDSS-Stripe 82 field (220 degree square) that has the advantage of being targeted by multiple deep imaging and spectroscopic surveys over the entire wavelength range. Benefitting from such exhaustive coverage and newly developed modelling techniques, the stellar and dust attenuation parameters computed for these galaxies are demonstrated to be the most accurate estimations as yet. In addition to that, multi-component models have been fitted on these galaxies to compute the full variety of structural parameters in the most consistent manner. Their investigation has revealed a well-defined trend between the dust attenuation and central concentration parameters of these galaxies. For disk-like galaxies ($n<2.0$), optical dust

attenuation parameter (R) covers a whole range of values. However, the more spheroid-like a galaxy is (n>4.0), the more constrained is the attenuation parameter. This suggests that all spheroid dominated galaxies have similar dust attenuation curves, thus, these can be approximated with reasonable accuracy. Current efforts are towards exploring the reason for the marked difference in the effects of dust for disk and spheroid dominated galaxies. This should also provide some insight regarding the time-scales for morphological transformation and dust production in galaxies over cosmic time.

[Sonali Sachdeva and Biman Nath]

Involvement of host galaxies in AGN jet origin

Over the last two decades, observations have demonstrated that nearly all galaxies, irrespective of their mass, harbour a supermassive black hole (SMBH) at their centres. An astonishing aspect of this discovery is that the mass of this SMBH is correlated with the properties (mass, luminosity and velocity dispersion) of the host galaxy, which is 6-7 orders-of-magnitudes larger in size. In Active Galactic Nuclei (AGN) also, more massive and actively accreting is the SMBH, the host galaxy is more likely to be a massive elliptical.

In confirmation, relativistic radio jets have been observed to be produced by massive AGNs living in elliptical galaxies. However, over the past decade, a large number (~500) of Narrow Line Seyfert1 (NLSy1) galaxies have been discovered to be producing relativistic radio jets. This poses a challenge to the understanding of jet origin because NLSy1 are low mass AGNs with disc dominated hosts. This challenge is aggravated by the detection of a significant fraction (10-20%) of this radio-loud sample (NLSy1-RL) in gamma rays, thus confirming the presence of jets. Resolving the reason for this counter-intuitive observation is crucial to understand the origin of jets. It is suspected that the host morphology is involved in fuelling and maintenance of these "young jets". To obtain concrete evidence, Sonali Sachdeva along with collaborators Rupjyoti Gogoi and Ravi Joshi performed detailed, multi-wavelength, multi-component structural decomposition of all NLSy1-RL galaxies (~45) observed with Subaru Hyper Supreme Camera. This involves careful modelling of the central source because even a slight mismatch results in the wrongful estimation of host galaxy parameters. In this work, the best representative PSF with different convolution sizes was applied to accurately model the central source.

They have now obtained all structural parameters representing the central source and sub-components of the host galaxy. Interestingly, host morphologies in the sample were found to be disturbed, with increased occurrence of spiral arms, bars, interaction signatures and double nuclei. Current efforts are towards the placement of these galaxies relative to the known BH-bulge relation for AGN and normal galaxies. They lend credence to the argument that hosts are majorly involved in the growth of these early jet systems.

[Sonali Sachdeva and collaborators Rupjyoti Gogoi (Tezpur University), Ravi Joshi (IIA)]

Theoretical modelling of two-component molecular discs in spiral galaxies

As recent observations of the molecular disks in spiral galaxies point to the existence of a diffuse, low-density thick molecular disk along with the prominent thin one, Narendra Nath Patra investigated the observational signatures of this thick disk by theoretically modeling two-component molecular disks in a sample of eight nearby spiral galaxies. Assuming a prevailing hydrostatic equilibrium, he set up and solved the joint Poisson's-Boltzman equation to estimate the three-dimensional distribution of the molecular gas and the molecular scale height in the sample galaxies. He found the molecular scale height in a two-component molecular disk to vary between 50 – 300 pc, which is higher than what is found in a single-component disk and that this scale height can vary significantly depending on the assumed thick disk molecular gas fraction. He also found that the molecular gas flares as a function of radius and follows a tight exponential law with a scale length of $(0.48 \pm 0.01)\ r_{25}$. He used density

solutions to produce the column density maps and spectral cubes to examine the ideal observing conditions to identify a thick molecular disk in galaxies and found that unless the molecular disk is an edge-on system and imaged with a high spatial resolution (less than or approximately equal to 100 pc), it is extremely hard to identify a thick molecular disk in a column density map. The spectral analysis further revealed that at moderate to high inclination (i greater than or approximately equal to 40°), spectral broadening can fictitiously introduce the signatures of a two- component disk into the spectral cube of a single-component disk. Hence, a low inclination molecular disk imaged with high spatial resolution would serve as the ideal site for identifying the thick molecular disk in galaxies. This work is now published: *Patra, N N, 2020b, A&A, 638, A66.*

[Narendra Nath Patra]

HI scale height in dwarf galaxies

Assuming a vertical hydrostatic equilibrium in the baryonic discs, joint Poisson's-Boltzmann equation was set up and solved numerically by Narendra Nath Patra for a sample of 23 nearby dwarf galaxies from the LITTLE-THINGS survey. This is the largest sample to date for which detailed hydrostatic modeling is performed. The solutions of the Poisson's-Boltzmann equation provide a complete three-dimensional distribution of the atomic hydrogen (HI) in these galaxies. Using these solutions, he estimated the vertical scale height (defined as the Half Width at Half Maxima (HWHM) of the density distribution) of the HI as a function of radius and found that the scale height in his sample galaxies varies between a few hundred parsecs at the center to a few kiloparsecs at the edge. These values are significantly higher than what is observed in spiral galaxies. He further estimated the axial ratios to investigate the thickness of the HI discs in dwarf galaxies and found for his sample galaxies, a median axial ratio to be 0.40, which is much higher than the same observed in the Milky Way. This indicates that the vertical hydrostatic equilibrium results in thicker HI discs in dwarf galaxies naturally. This work is now published: *Patra, N.N, 2020a, MNRAS, 495, 2867.*

[Narendra Nath Patra]

HI scale height in spiral galaxies

During the past year, Narendra Nath Patra modelled the galactic discs of seven nearby large spiral galaxies as three-component systems consisting of stars, molecular gas, and atomic gas in vertical hydrostatic equilibrium. Corresponding joint Poisson-Boltzmann equations were set up and solved numerically to estimate the three-dimensional distribution of HI in these galaxies. While solving the Poisson-Boltzmann equation, instead of considering a constant HI velocity dispersion (σHI); he developed an iterative method to self-consistently estimate the σHI profile in a galaxy by using the observed second-moment profile of the HI spectral cube. Using the density solutions, the HI vertical scale height in the galaxies was determined. He found that the HI discs flare in a linear fashion as a function of radius. HI scale height in his galaxies was found to vary between a few hundred parsecs at the center to ~ 1 – 2 kpc at the outskirts. A median ratio of 0.1 was estimated for the axial ratio of the HI discs in the sample galaxies, which is much lower than what is found for dwarf galaxies, indicating much thinner HI discs in spiral galaxies. Very low axial ratios in three of his sample galaxies (NGC 5055, NGC 6946 , and NGC 7331) suggest them to be potential super-thin galaxies. Using the HI distribution and the HI hole sizes in NGC 6946, he found that most of the HI holes in this galaxy are broken out into the circumgalactic medium and this breaking out is more effective in the inner radii as compared to the outer radii.This work is now published: *Patra, N N, 2020, MNRAS, 499, 2063.*

[Narendra Nath Patra]

Thick disk molecular gas fraction in NGC 6946

Several recent studies reinforce the existence of a thick molecular disc in galaxies along with the dynamically cold thin disc. Assuming a two-component molecular disc, Narendra Nath Patra modelled the disc of NGC 6946 as a four-component system consisting of stars, HI, thin disc molecular gas, and thick disc molecular gas in vertical hydrostatic equilibrium. Following, he set up the joint Poisson-Boltzmann equation of hydrostatic equilibrium and solved it numerically to obtain a three-dimensional density distribution of different baryonic components. Using the density solutions and the observed rotation curve, he further built a three-dimensional dynamical model of the molecular disc and consecutively produced simulated CO spectral cubes and spectral width profiles. He found that the simulated spectral width profiles distinguishably differ for different assumed thick disc molecular gas fractions. Several CO spectral width profiles were then produced for different assumed thick disc molecular gas fractions and compared with the observed one to obtain the best fit thick disc molecular gas fraction profile. This revealed that the thick disc molecular gas fraction in NGC 6946 largely remains constant across its molecular disc with a mean value of 0.70 ± 0.09. He also estimated the amount of extra-planar molecular gas in NGC 6946 and found ~ 50% of the total molecular gas is extra-planar at the central region, whereas this fraction reduces to ~ 15% at the edge of the molecular disc. With this method, for the first time, an estimate for the thick disc molecular gas fraction as a function of radius in an external galaxy with sub-kpc resolution was achieved. This work is now published: *Patra, N N, 2021, MNRAS, 501, 3527*

[Narendra Nath Patra]

High Energy Astrophysics

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

PeV-EeV neutrinos from gamma-ray blazars due to ultrahigh-energy cosmic-ray propagation

Blazars are potential candidates of cosmic-ray acceleration up to ultrahigh energies ($E \geq 10^{18}$ eV). For an efficient cosmic-ray injection from blazars, $p\gamma$ collisions with the extragalactic background light (EBL) and cosmic microwave background (CMB) can produce neutrino spectrum peaks near PeV and EeV energies, respectively. Saikat Das, Nayantara Gupta and collaborator Soebur Razzaque analyzed the contribution of these neutrinos to the diffuse background measured by the IceCube neutrino observatory. The fraction of neutrino luminosity originating from individual redshift ranges was calculated using the distribution of BL Lacs and FSRQs provided in the Fermi-LAT 4LAC catalog. Furthermore, they used a luminosity dependent density evolution to find the neutrino flux from unresolved blazars. The results obtained with their model indicated that as much as $\cong$ 10% of the flux upper bound at a few PeV energies can arise from cosmic-ray interactions on EBL. The same interactions will also produce secondary electrons and photons, initiating electromagnetic cascades. The resultant photon spectrum is limited by the isotropic diffuse γ-ray flux measured between 100 MeV and 820 GeV. The latter, together with the observed cosmic-ray flux at $E > 10^{16.5}$ eV, can constrain the baryonic loading factor depending on the maximum cosmic-ray acceleration energy. This work is published in: *Saikat Das et al 2021 ApJ 910 100.*

[Saikat Das, Nayantara Gupta and collaborator Soebur Razzaque (University of Johannesburg, South Africa)]

Study of Temporal and Spectral variability for Blazar PKS 1830-211 with Multi-Wavelength Data

A study of the gravitationally lensed blazar PKS 1830-211 was carried out by Nayantara Gupta and collaborators Jayant Abhir, Raj Prince, Jophin Joseph and Debanjan Bose using multi waveband data collected by Fermi-LAT, Swift-XRT and Swift- UVOT telescopes between MJD 58400 to MJD 58800 (9 Oct 2018 to 13 Nov 2019). Flaring states were identified by analysing the gamma-ray light curve. Simultaneous multi-waveband SED were obtained for those flaring periods. A cross-correlation analysis of the multi-waveband data was carried out, which suggested a common origin of the gamma-ray and X-ray emission. The broadband emission mechanism was studied by modelling the SED using a leptonic model. Physical parameters of the blazar were estimated from the broadband SED modelling. The blazar PKS 1830-211 is gravitationally lensed by at least two galaxies and has been extensively studied in the literature because of this property. The self-correlation of the gamma-ray light curve was studied to identify the signature of lensing, but no conclusive evidence of correlation was found at the expected time delay of 26 days. This work is now published: *J. Abhir et al 2021 ApJ 915 26*

[Nayantara Gupta and collaborators Jayant Abhir (IIT, Kharagpur), Raj Prince (CTP, Poland), Jophin Joseph (IIT, Kharagpur), Debanjan Bose (S N Bose Institute, Kolkata)]

Multi-wavelength Analysis and Modeling of OJ 287 During 2017-2020

The blazar OJ 287 has been proposed as binary black hole system based on its periodic optical outburst. Among blazars with parsec scale jets, the black hole binary systems are very rare and hence this source is very interesting to study. The BL Lac OJ 287 is an interesting object for multi-wavelength study due to its periodic outbursts. Aditi Agarwal, Nayantara Gupta and collaborators Raj Prince, Pratik Majumdar, Bozena Czerny, Sergio A Cellone and I Andruchow analysed the optical, X-ray and gamma-ray data of OJ 287 for the period of 2017 – 2020 . They found several high states in optical-UV and X-ray frequencies during this period. Based on the observed variability in optical and X-ray frequencies the entire period 2017 – 2020 was divided in five segments, referred as A, B, C, D and E. Detailed temporal and spectral analysis was performed to understand the nature of its flaring activities. To understand the temporal variability in this source they studied the intra-day, and fractional variability for all the various states, and along with that fast variability time was also estimated to understand the nature of variability. Further, the multi-wavelength SED modeling was performed to know more about the physical processes responsible for the simultaneous broadband emission and the fast variability. The Fermi LAT observations revealed a moderate flux level of this source in gamma- ray frequency throughout this period. The source showed a strong flux variability in X-ray, optical, and UV during May 2020 when the source was in very high state. A single zone emission model was considered to model the spectral energy distributions which will help in exploring the nature of this BL Lac with binary super-massive black holes. This work is now published: *https://doi.org/10.1051/0004-6361/202140708*

[Aditi Agarwal, Nayantara Gupta and collaborators Raj Prince (CTP, Poland), Pratik Majumdar (SINP, Kolkata), Bozena Czerny (CTP, Poland), Sergio A Cellone (Univ. Nacional de La Plata, Argentina), I Andruchow (Univ. Nacional de La Plata, Argentina)]

Spectral modeling of Flares in Long Term Gamma-Ray Light Curve of PKS 0903-57

A detailed study of the BL Lac PKS 0903-57 was done for the first time by Sandeep Kumar Mondal, Nayantara Gupta, Avik Das and collaborator Raj Prince with 12 years of Fermi-LAT data. Two bright gamma- ray flares in 2018 and 2020 were identified and defined as 'Flare-1' & 'Flare-2' respectively. Many sub-structures were observed during multiple time binning. Detailed temporal and spectral study on all the sub-structures separately were performed. A single-zone emission model was used for time-dependent leptonic modeling of the multi-wavelength SEDs. This work includes estimated values of variability time scale, magnetic field

in the emission region, jet power obtained from leptonic modeling of PKS 0903-57. Owing to the minimal number of observations in X-rays and other bands more simultaneous multi-wavelength monitoring of this source is required to have a better understanding of the physical processes happening in the jet of the blazar PKS 0903-57. A pre-print is available: *arXiv:2107.02702*

[Sandeep Kumar Mondal, Nayantara Gupta, Avik Das and collaborator Raj Prince (CTP, Poland)]

Multi wavelength study of 4C+28.07

4C+28.07 is a γ-ray FSRQ type source. It is often monitored at different frequencies, though long term multi-wavelength data of this source have not been modelled in detail before. Avik Das and Nayantara Gupta along with collaborator Raj Prince have analyzed ~12 years (Aug, 2008 -May, 2020) Fermi-LAT data with a binning of 10 days time scale and observed three distinctive flaring states. Each flaring state consisted of different phases of activity, namely, pre-flare, flare & post-flare regions. γ-ray spectral analysis of these different activity phases has been performed and the best fit model for its spectra is found to be a Log-parabola model. They also studied the correlation of simultaneous γ-ray light curves with the optical & radio counterparts in these flaring states and reported the DCF with 95% significant level. A large time delay was found between radio and gamma ray data for two flares, indicating two zones of emission. The multi-wavelength data was fitted with two zone leptonic model. In the two zone leptonic model the maximum required power in the jet is 9.64×10^{46} erg sec^{-1}, which is lower than its Eddington luminosity 2.29×10^{47} erg sec^{-1}. A pre-print is available: *arXiv:2107.10555*

[Avik Kumar Das, Nayantara Gupta and collaborator Raj Prince (CTP, Poland)]

Broadband Modelling of Orphan Gamma Ray Flares

Blazars, a class of highly variable active galactic nuclei, sometimes exhibit Orphan γ-ray flares. These flares having high flux only in γ-ray energies do not show significant variations in flux at lower energies. Nayantara Gupta and collaborators S R Patel, D Bose and M Zuberi studied the temporal and spectral profile of these Orphan γ-ray flares in detail from three γ-ray bright blazars, 3C 273, PKS 1510-089 and 3C 279 and also their simultaneous broadband emissions and found that the variability timescales of the Orphan γ-ray flares were (0.96±0.28) days, (3.12±2.40) hr and (2.16±0.72) hr, for 3C 273, PKS 1510-089 and 3C 279, respectively. The broadband spectral energy distributions (SEDs) during these flares were modelled with a leptonic model from two emission regions. This model suggests that Orphan γ-ray flares might have originated from inverse Compton scattering of relativistic electrons by the seed photons from the broad-line region or dusty torus, which is the first region. While the second broader region, lying further down the jet, could be responsible for X-ray and radio emissions. The possible locations of these emission regions in the jets of the three sources were estimated from SED modelling. This work is now published: *Journal of High Energy Astrophysics, 2021, Vol.29, p31–39.*

[Nayantara Gupta and collaborators S R Patel (University of Mumbai, Mumbai), D Bose (IIT, Kharagpur), M Zuberi (TIFR, Mumbai)]

Multi-wavelength studies of AGNs

Small bright regions in the center of massive galaxies having bolometric luminosities between 10^{41}–10^{48} erg s^{-1} are called active galactic nuclei (AGNs). A small fraction of AGNs are associated with powerful Doppler boosted jets. One such sub-class of AGNs characterized by non-thermal radiation over entire electromagnetic (EM) spectra and having jets pointing at a line of sight angle of ≤ 10 degrees are known as blazars. Aditi Agarwal has contributed to our understanding of complex phenomena occurring at the centers of these

extraordinary galaxies using analytical, observational, and computational techniques. Using the multi-wavelength data of these sources on diverse timescales, she has probed the location and physical processes related to: the emission mechanisms dominant in these sources, search for the presence of quasi-periodic oscillations, discern flare characteristics, and estimate supermassive black hole mass. Finally, combining the observational results with the theoretical models helped in the understanding of the physics governing these objects. Analysis of a recently observed flare (one of the strongest flares observed) from a blazar named BL Lacertae from August 2020 to March 2021 is currently underway. This could help probe the mysteries at different stages of the evolution of the Universe.

[Aditi Agarwal, Nayantara Gupta and collaborators G. C Anupama (IIA, Bengaluru), C S Stalin: (IIA, Bengaluru), Sergio A Cellone (CASLEO, Argentina), Dr. Ileana Andruchow (CASLEO, Argentina), Staszek Zola (Astronomical Observatory, Poland), B Mihov (Institute of Astronomy and NAO, Sofia, Bulgaria, L Slavcheva-Mihova (Institute of Astronomy and NAO, Sofia, Bulgaria), Raj Prince –(CTP, Poland), Priyanka Rani (IUCAA, Pune), Aykut Ozdonmez (Istanbul University, Turkey) and Ergun Ege (Istanbul University, Turkey)]

Cosmology

Shiv Sethi's work during this period could be divided into mainly two categories: (a) Detection of Neutral hydrogen (HI) at high redshifts and the study of redshifted HI emission from the epoch of reionization, and (b) Probes of alternative dark matter models using cosmological observables.

Analysis of MWA drift scan data for detecting EoR

One of the main stumbling block in the detection of fluctuating component of the redshifted HI signal from EoR is the changing systematics, e.g. bandpass, primary beam, etc., during the observational run. In a drift scan, one expects the system to be stable as no electronic delays are introduced for telescopes such as MWA during a run. By the analysis of 55 hours of MWA data with repeated scans of nearly five hours each night, Shiv Sethi, Akash Patwa and K S Dwarakanath have shown that the system remains fairly stable for nearly 5 hours of run by comparing the data power spectrum with noise simulations. They also characterized foregrounds during a drift scan. Computing the HI power spectrum from the data showed that their results are the best upper limits of $k \cong 1$ Mpc^{-1}.

[Akash Patwa, K S Dwarakanath and Shiv Sethi]

Energy injection in the pre-recombination era and EDGES result

EDGES result has opened the possibility of energy injection in the early universe. Shiv Sethi along with students Nirmalya Brahma and Shivnag Sista explored this possibility by considering energy injection from the decay of a dark matter particle close to the era of recombination and showed that this is the only viable route to explain the EDGES result through a pre-recombination era energy injection. Most of the injected photons are absorbed by free-free absorption and pumped into CMB thereby causing CMB spectral distortion. They developed a formalism to study these processes and showed such an energy injection can explain the EDGES result and its presence can be revealed by the future CMB spectral distortion experiments.

[Shiv Sethi and IISc undergraduates: Nirmalya Brahma and Shivnag Sista]

Post Reionization Era and the Large Scale Structure of the Universe

Studying the post-reionization era constitutes an important area of research in modern-day cosmology. In this era, bulk of the neutral hydrogen (HI) resides in those dense pockets within the galaxies that have HI column number densities $N_{HI} \geq 2 \times 10^{21}$ atoms/cm^2. These regions are identified as the damped Lyman Alpha (DLAs) in quasar observations. Different from the galaxy surveys, observations of the HI 21-cm signal do not resolve the individual HI sources, and the collective emission from these sources appear as background radiation in HI 21-cm observations. Fluctuations in this background radiation carries the imprint of the underlying source clustering at that epoch. These fluctuations are ordinarily quantified using a quantity called the HI power spectrum, which gives the correlations of the HI fluctuations measured in Fourier space. Measuring the HI power spectrum can help address several issues related to the HI distribution and the formation of the large scale structure in the universe.

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

Summary of the works carried out under this broad research theme in 2020-21 follows.

Using redshift evolution of the Lyman- opacity as a probe of dark matter models

Anjan Sarkar and Shiv Sethi along with collaborator Kanhaiya Pandey have explored the redshift evolution of the observable effective optical depth eff(z) from the Lyman data as a discriminator between dark matter models that differ from the CDM model on small scales. Thermal warm dark matter (WDM) and the ultra-light axion (ULA) models with the following masses: the ULA mass, $m_a = 10^{-24}$ - 10^{-22} eV and the WDM mass, $m_{wdm} = 0.14.6$ keV respectively were considered. Line-of-sight HI density and velocity fields were simulated using semi-analytic methods. The simulated effective optical depth for the alternative dark matter models showed deviations from that for the ΛCDM model at redshifts $z \geq 3$. This gives a meaningful way to distinguish the alternative dark matter models from the standard CDM model. Using the method of likelihood analysis, they compared the simulated data with the available high-resolution Lyman-α cloud data in the redshift range $2 \leq z \leq 4.2$. The 1D posterior probabilities of the WDM and the ULA masses was found to peak at $m_a = 5 \times 10^{-23}$ eV and $m_{wdm} = 1.1$ keV respectively. The 1D posterior probabilities for the WDM and the ULA models remained flat for larger masses, indicating that the Lyman-α data are compatible with the ΛCDM model.

[Anjan Sarkar, Shiv Sethi and collaborator Kanhaiya Pandey (ICTS, Bengaluru)]

Probing f(R) gravity using the post-reionization HI 21-cm signal

Anjan Kumar Sarkar and collaborators Chandrachud B V Dash and Tapomoy Guha Sarkar have proposed the intensity mapping of the redshifted HI 21-cm signal from the post-reionization epoch as a cosmological probe of f(R) gravity. They considered the Hu-Sawicki family of f(R) gravity models characterized by a single parameter $f_{,Ro}$. The f(R) modification to gravity affects the post-reionization 21-cm power spectrum through the change in the growth rate of density fluctuations. The quantity of interest is the redshift space distortion parameter T (k, z) which imprints the change. They

found that a radio interferometric observation at an observing frequency 710 MHz with a SKA-1-Mid like radio telescope may measure the binned T(k) at a level of sensitivity to distinguish f(R) models with $\log_{10}|f_{,R_0}| > 5$ at a $> 5\sigma$ level in the k range $k > 0.4$ Mpc^{-1}. They found that using a Fisher matrix analysis the 1-σ bound obtained on the parameter is $5.62 < \log_{10}|f_{,R_0}| < 4.38$ which is competitive with other probes of f(R) gravity.

Thus the future observation of the post-reionization HI signal holds the potential to put robust constraints on f(R) gravity models and enrich our understanding of late time cosmic evolution and structure formation.

[Anjan Kumar Sarkar and collaborators from BITS Pilani: Chandrachud B V Dash and Tapomoy Guha Sarkar]

Observational Cosmology Using 21-cm Line from Neutral Hydrogen

Saurabh Singh's primary field of interest is observational cosmology using 21-cm line from neutral hydrogen and he works with instruments that aim to trace this line to uncover the underlying science. When observed in the near Universe (redshifts < 3), 21-cm line is a probe of the large-scale structure. This allows us to characterize one of the standard rulers: baryon acoustic oscillations, and constrain one of the most elusive components of the Universe: dark energy. When we observe the 21-cm line in the far Universe (redshifts > 6), it is a probe of nature of first stars and galaxies, whose radiation subsequently re-ionized the whole Universe. Therefore, detection of 21-cm line over different times in the evolution of the Universe is an all-inclusive probe of astrophysics and cosmology.

Precision measurement of the 21-cm line over a range of redshifts is challenging due to orders of magnitude bright emissions from our own Galaxy and other extragalactic sources. Additionally, ionosphere, terrestrial radiation, and interaction of the instrument with the sky signal creates another set of challenges, all of which require an accurate modelling of around 0.001% to be able to uncover the underlying faint 21-cm cosmological signal.

In order to address these challenges, Saurabh Singh's efforts are focused on design and characterization of custom-built radio telescopes for 21-cm cosmology, along with development of statistical techniques to derive the cosmological inferences from the data.

During the past year Saurabh Singh's research efforts were geared towards 21-cm cosmology targeting different redshifts.

Hydrogen Epoch of Reionization Array (HERA)

HERA observes in the frequency range of 50-250 MHz, with an aim to detect 21-cm signal from the cosmic dawn and epoch of reionization. Saurabh Singh's work is centred on forming statistical estimates of the data to constrain the properties of the first stars and galaxies. This work was done in collaboration with Adrian Liu. They investigated the power spectrum estimation as one of the statistical estimates for cosmology. Over the last year, he worked on improving the power estimation algorithms, along with performing statistical tests on the data to look for possible contamination from the instrument. The resulting work, as part of the collaboration, has resulted in one of the most sensitive upper-limits on 21-cm signal, and is in the review process.

[Saurabh Singh and Adrian Liu (McGill University, Canada), HERA Collaboration]

Canadian Hydrogen Intensity Mapping Experiment

CHIME observes in 400-800 MHz, aiming to detect 21-cm power spectrum to map the large-scale structure, and constrain the nature of dark energy. Saurabh Singh's efforts during the past year revolved around modeling the primary beam of the telescope, which has complex

spatial and spectral features due to non-trivial interactions between different antenna elements. This work was carried out in collaboration with Matt Dobbs and Gary Hinshaw. Given the high volume of data, ~1 TB/day, Saurabh Singh developed automated tasks to perform data quality assessment, which is an essential tool in selecting datasets to enhance sensitivity. The scientific requirements for cosmology also match the requirements for detecting radio transients. One of the most elusive transients is referred to as Fast Radio Bursts (FRB). CHIME has had several detections of them, and an article on the resulting catalogue of detections has been submitted. He also worked with the signal injection team of CHIME/FRB to better understand how the intrinsic nature of these transient bursts are modified while interacting with the telescope.

[Saurabh Singh, Matt Dobbs (McGill University, Canada) and Gary Hinshaw (University of British Columbia, Canada), CHIME collaboration]

Shaped antenna measurement of the background radio spectrum 3

The latest version of the SARAS instrument observes between 50-100 MHz with an aim to cross-verify a detection of 21-cm signal from EDGES collaboration. The detection was anomalous in its amplitude and profile, defying all the standard predictions. Over the last year, Saurabh Singh worked towards performing calibration and statistical inference on the data. This work was carried out in collaboration with Ravi Subrahmanyan, N Udaya Shankar and Jishnu Nambissan T. Jishnu Nambissan investigated methods to model and/or subtract out systematics introduced by the receiver from observational data as well as analysis of data. An article on these results is currently under review.

[Saurabh Singh, Ravi Subrahmanyan (CSIRO Astronomy & Space Science, Australia), N Udaya Shankar, Jishnu Nambissan T, Mayuri S Rao along with other members of CMB Distortion lab at RRI]

Observational Astronomy

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

Radio Astronomy

Gas mass of star-forming galaxies at $z \approx 1$

Using uGMRT data Shiv Sethi and K S Dwarakanath along with collaborators Aditya Chowdhury, Nissim Kanekar and Jayaram Chengalur searched for HI emission from star-forming galaxies in the redshift range $0.7 < z < 1.35$. These galaxies lie in the sub-fields of DEEP2 optical redshift survey. Using these redshifts, they shifted the spectra of nearly 7000 galaxies to the rest frame of 21 cm emission and coadded them. This allowed them to reach an unprecedented noise level of nearly 1 μJy in the coadded spectrum and gave a 4.7σ detection of HI at $z \approx 1$. This is the first such detection of HI in emission at high redshifts.

[Aditya Chowdhury, Nissim Kanekar, Jayaram Chengalur from NCRA, Pune and K S Dwarakanath and Shiv Sethi]

Extra-planar radio emission from star forming disc galaxies

Biman Nath, Aditi Vijayan, K S Dwarakanath and collaborator Ruta Kale observed a nearby edge-on star forming galaxy (NGC 4631) in order to compare the simulation results of Aditi Vijayan with observations. Currently they are in the process of analysing the data.

[Aditi Vijayan, Biman Nath, K S Dwarakanath and collaborator Ruta Kale (NCRA, Pune)]

Non-thermal SZ effect from radio galaxy cocoons

With collaborators S Acharya and S Majumdar, Biman Nath studied the non-thermal SZ signal from radio galaxy cocoons, since these cocoons are likely filled with high energy particles produced in the radio jet. They have also studied how these signals could be detected in the experiments that are planned for the near future.

[Biman Nath and collaborators from TIFR, Mumbai: S Acharya and S Majumdar]

Ultraviolet Astronomy

Comparing the inner and outer star forming complexes in the nearby spiral galaxies NGC 628, NGC 5457 and NGC 6946 using uv observations

K S Dwarakanath and Narendra Nath Patra along with collaborators Jyoti Yadav, Mousumi Das, P T Rahna, Stacy S McGaugh, James Schombert and Jayant Murthy undertook a far-UV (FUV) study of the star-forming complexes (SFCs) in three nearby galaxies using the Ultraviolet Imaging Telescope (UVIT). The galaxies are close to face-on and show significant outer disk star formation. Two of them are isolated (NGC 628, NGC 6946), and one is interacting with a distant companion (NGC 5457). They compared the properties of the SFCs inside and outside the optical radius (R25) and estimated the sizes, star formation rates (SFRs), metallicities, and the Toomre Q parameter of the SFCs. They found that the outer disk SFCs are at least ten times smaller in area than those in the inner disk. The SFR per unit area in both regions had similar mean values, but the outer SFCs had a much smaller range of SFR per unit area. They were also metal-poor compared to the inner disk SFCs. The FUV emission is well correlated with the neutral hydrogen gas (HI) distribution and was detected within and near several HI holes over the disks. Estimation of the Q parameter in the outer disks of the two isolated galaxies suggested that their outer disks are stable (Q greater than 1). However, their FUV images indicates that there is ongoing star formation in these regions. This suggests that there may be some non-luminous mass or dark matter in their outer disks, which increases the disk surface density and thus supports the formation of local gravitational instabilities. In the interacting galaxy, NGC 5457, the baryonic surface density was found to be sufficient (Q less than 1) to trigger local disk instabilities in the outer disk.

[Jyoti Yadav (IIA, Bengaluru), Mousumi Das (IIA, Bengaluru), Narendra Nath Patra, K S Dwarakanath, P T Rahna (SAO, China), Stacy S McGaugh (CWRU, USA), James Schombert (U Oregon, USA) and Jayant Murthy (IIA, Bengaluru)]

A Comparison of the UV and HI properties of the extended UV (XUV) disk galaxies NGC 2541, NGC 5832 and ESO406-042

K S Dwarakanath, Narendra Nath Patra and collaborators Mousumi Das, Jyoti Yadav, Stacy McGaugh, James Schombert, P T Rahna and Jayant Murthy, undertook a UV study of 3 extended UV(XUV) galaxies observed with the UVIT and the GMRT. XUV galaxies show filamentary or diffuse star formation well beyond their optical disks, in regions where the disk surface density lies below the threshold for star formation. GALEX observations found that surprisingly 30 percent of all the nearby spiral galaxies have XUV disks. The XUV galaxies can be broadly classified as type 1 and

type 2 XUV disks. The type 1 XUV disks have star formation that is linked to that in their main disk, and the UV emission appears as extended, filamentary spiral arms. The UV luminosity is associated with compact star forming regions along the extended spiral arms. The star formation is probably driven by slow gas accretion from nearby galaxies or the intergalactic medium (IGM). But the type 2 XUV disks have star formation associated with an outer low luminosity stellar disk that is often truncated near the optical radius of the galaxy. The nature of the stellar disks in type 2 XUV disks are similar to that of the diffuse stellar disks of low surface brightness galaxies. The star formation in type 2 XUV disks is thought to be due to rapid gas accretion or gas infall from nearby high velocity clouds (HVCs), interacting galaxies or the IGM. They also investigated the star formation properties of the XUV regions of two type 2 galaxies and one mixed XUV type galaxy and compared them with the neutral hydrogen (HI) emission in their disks. Preliminary results of UVIT (FUV and NUV) observations of NGC 2541, NGC 5832 and ESO 406-042, as well as GMRT observations of their HI emission resulted from this work. This work also includes a description of the UV emission morphology, estimation of the star formation rates and comparison with the HI distribution in these type 2 and mixed XUV galaxies.

[Mousumi Das (IIA, Bengaluru), Jyothi Yadav (IIA, Bengaluru), Narendra Nath Patra, K S Dwarakanath, Stacy McGaugh (CWRU, USA), James Schombert (U. Oregon, USA), P T Rahna (SAO, China), Jayant Murthy (IIA, bengaluru)]

X-ray Astronomy

Compact X-ray binaries are composed of a compact object, a neutron star or a black hole and a companion 'normal' star. The intense gravitation field of the neutron star causes matter from the companion star to accrete onto the neutron star, producing X-rays. X-ray astronomy is a powerful tool to study such objects. A plethora of information about system parameters like magnetic field geometry and strength, chemical composition of the surrounding medium and dynamics like orbital period and radius evolution of X-ray binaries, structural evolution of the accretion disk and its time scales, and structure in the stellar winds can be obtained by a careful analysis of the X-ray output from compact X-ray binaries. A brief overview of various aspects of compact X-ray sources investigated by RRI astronomers during 2020-21 is given below.

Investigation of Various Aspects of Compact X-ray Sources

Broad-band X-ray characteristics of the transient pulsar GRO J2058+42

The Be X-ray binary GRO J2058+45 recently went through a Type-II outburst during 2019 March-April lasting for about 50 d. This outburst was detected with all the operating all sky X-ray monitors like the Fermi-GBM, Swift-BAT, and MAXI-GSC. Two pointed observations were also made with the Nuclear Spectroscopic Telescope Array (NuSTAR), one during the rise and other during the decay of the outburst. It gave Sanhita Kabiraj and Biswajit Paul an opportunity to analyse the broad-band characteristics of the pulsar for the first time and to investigate the accretion torque characteristics of the pulsar over a wide range of X-ray luminosity. The pulse profile was found to be strongly energy-dependent, with at least four different pulse components at low energy (< 20 keV), to a single-peaked profile at high energy (> 30 keV). In each of the narrow energy bands, the pulse profile was nearly identical in the two NuSTAR observations. The spectra from both the observations were fitted well to a power-law with a Fermi-Dirac-type high-energy cutoff. Their analysis ruled out the presence of a cyclotron line in the pulse phase averaged X-ray spectrum in the NuSTAR band with an optical depth greater than 0.15. An iron emission line was detected in both the NuSTAR spectra with an equivalent width of about 125 eV. A careful look at the dependence of the spin-up rate on the

luminosity enabled them to estimate the magnetic field strength from that, which came out to be much higher compared to other known BeXRB pulsars. In the context of these results, they also studied the inadequacy of the torque-luminosity relation for determination of magnetic field strength of neutron stars.

[Sanhita Kabiraj and Biswajit Paul]

New measurements of the cyclotron line energy in Cen X-3

Analysis of data from two observations of the accreting binary X-ray pulsar Cen X-3 made with the broad-band X-ray observatories Suzaku and NuSTAR was carried out during the past year by Gunjan Tomar, Biswajit paul and collaborator Pragati Pradhan. The pulse profile was found to be dominated by a broad single peak and showed some energy dependence with two additional weak pulse peaks at energies below 15 and 25 keV, respectively. The broad-band X-ray spectrum covering 0.8-60.0 keV for Suzaku and 3.0-60.0 keV for NuSTAR fitted well with high-energy cut-off power-law model along with soft-excess, multiple iron emission lines and a cyclotron absorption. The cyclotron line energy was found to be ~30.3 keV and ~29.2 keV respectively, in the Suzaku and NuSTAR spectra. A comparative study of these two measurements with four previous measurements of Cyclotron Resonant Scattering Feature (CRSF) in Cen X-3 obtained with Ginga, BeppoSAX, and RXT showed no evidence for a dependence of the CRSF on luminosity. Except for one CRSF measurement with BeppoSAX , the remaining measurements were consistent with a CRSF energy in the range of 29.5-30.0 keV over a luminosity range of 1.1-5.4 x 10^{37} erg s^{-1}, different from several other sources that show considerable CRSF variation in the same luminosity range.

[Gunjan Tomar, Pragati Pradhan (Massachusetts Institute of Technology, USA) and Biswajit Paul]

Thermonuclear X-ray bursts detected in Cyg X-2 using AstroSat-LAXPC

Biswajit Paul along with collaborators Jincy Devasia and Gayathri Raman detected five Type-1 thermonuclear X-ray bursts and one burst-like event in the neutron star LMXB source Cyg X-2 using X-ray data obtained with the Large Area X-ray Proportional Counter (LAXPC) instrument on board AstroSat. An energy resolved burst profile analysis as well as time resolved spectral analysis for each of the bursts was carried out and their properties characterized. All bursts were found to be weak with burst peak-to-persistent intensity ratio < 3, decay time ~1.2 s, and with fluence ~ $1x10^{-8}$ ergs/cm^2, indicating that the observed bursts are Helium fuelled flashes. An evolution of the blackbody temperature and radius was also observed during each burst. They carried out a search for Burst Oscillations (BO) and derived upper limits to the rms fractional amplitude for BO (for all the bursts) to be ~ 1%. They also carried out search for Quasi Periodic Oscillations (QPOs) in the power density spectra and obtained upper limits to the fractional rms amplitude as ~3.4% at frequencies close to ~5.6 Hz. Spectral and timing analysis of the non-burst persistent emission along with a study of the hardness-intensity and colour-colour diagrams also formed part of the study. Using results from the analysis they inferred that during this observation in 2016, Cyg X-2 can be characterized as being in the early Flaring Branch (FB) with a puffed up accretion disk and a clumpy coronal structure while undergoing medium-to-high levels of accretion.

[Jincy Devasia (Henry Baker College, Kottayam), Gayathri Raman (IIT, Bombay) and Biswajit Paul]

Comprehensive broad-band study of accreting neutron stars with Suzaku: A bi-modality in the X-ray spectrum

Broad-band spectral analysis of accreting neutron stars was carried out by Biswajit Paul and collaborators Pragati Pradhan, Enrico Bozzo, Chandreyee Maitra and B C Paul using data from XIS and PIN onboard the Suzaku observatory. From spectral fits of these sources with a single continuum model including a power law

and high energy cut-off, cyclotron lines (where required), they studied the correlation between various spectral parameters. Among 39 sources studied, 16 of those were ones where the existence of a cyclotron line is known in literature, and 29 have a cut-off energy in their X-ray spectra. Among these 29 sources, 18 have cut-off energy bunched in a range of 3-10 keV while for 11 sources, it spreads over 12-25 keV. This bi-modal behaviour was not based on the specific nature of the systems being a Be XRB or supergiant HMXB, nor on different beaming patterns characterizing their X-ray emission as inferred from simultaneous study of their pulse profiles. The broad-band coverage of Suzaku also showed that the cut-off energies saturate for higher values of cyclotron line energies – consistent with previous works in literature – for both the groups the width of the cyclotron line showed a weak correlation with the cyclotron line energy. An anti-correlation with luminosity for both spectral index and folding energy, respectively was also found. Unlike previous works, they did not detect any anti-correlation between X-ray luminosity and EW of K α lines. Finally, they showed that the EW and flux of the iron K α line are smaller in SFXTs than classical NS-HMXBs. These findings were discussed in terms of different properties of stellar winds and accretion mechanisms.

[Biswajit Paul and collaborators Pragati Pradhan (MIT, USA), Enrico Bozzo (ISDC, University of Geneva), Chandreyee Mairta (Max Planck Institute for Extraterrestrial Physics, Germany), B C Paul (North Bengal University, West Bengal)]

Cataclysmic Variable Systems and Ultra-Luminous X-ray Sources

With his PhD students Anirban Dutta and Tanuman Ghosh, Vikram Rana is working on several Cataclysmic Variable (CV) systems and Ultra-luminous X-ray sources (ULXs) utilizing data from the NuSTAR, XMM-Newton and other X-ray observatories. He is also a part of AstroSat caltaclysmic variables science team. During the past year an interesting result on a CV, AR Sco using observations from Chandra and AstroSat observatories was published. Another area of focus during the past tear was ultraluminous X-ray sources, in particular detailed work on NGC 4190 ULX1 studying its timing and spectral properties using XMM-NEWTON archival data. This resulted in an publication. Current efforts are towards studying NGC 891 galaxy that hosts three ULXs and preparing that work for publication.

[Anirban Dutta, Tanuman Ghosh and Vikram Rana]

Experimental Astronomy

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

Epoch of Reionization

PRATUSH

Probing Reionization of the Universe using Signal from Hydrogen is a proposed radiometer in lunar orbit that will reveal the Cosmic Dawn of our Universe. Observing the radio sky over 30-220 MHz over the far-side of the moon with high sensitivity, PRATUSH will answer the question of when the first stars formed in our universe, the nature of the first stars, and what was the light from the first stars or, in other words, the

Figure 1. PRATUSH design (55 - 110 MHz). A monopole antenna over a profiled reflector on a customized cubesat bus (courtesy Kavitha K, A Raghunathan, PRATUSH team)

colour of the light of Cosmic Dawn. PRATUSH will be the pioneering space telescope that will reveal, for the first time, the history of our infant Universe as it transformed after the Big Bang – from cold gas into stars and galaxies and the universe as we know it today. PRATUSH, as its name denotes, will inform us of the first rays of the first suns in the infant Universe. The proposal for PRATUSH was submitted jointly by members of RRI CMB DISTORTION Lab in response to an announcement of opportunity for science payloads from ISRO. PRATUSH has been funded by ISRO for pre-project studies mode over 2019-2021.

Mayuri S Rao has led the project jointly with Saurabh Singh and Jishnu Nambissan T, along with her lab members that are all heavily involved in the experiment. They have in the past year finalized several design aspects of PRATUSH, including arriving at a baseline antenna design, analog receiver architecture, hardware tests, digital receiver development, control and acquisition through a commercial Single Board Computer, realizing a custom Vector Network Analyzer. Efforts during the past year were on the system design, calibration methods, architecture, and integration of PRATUSH. Furthermore, Mayuri S Rao has been involved in investigating secondary science goals for PRATUSH in lunar as well as Low Earth Orbit (LEO). She is also heavily involved in continued engagement with ISRO documentation and in guiding the research associates working with the group. A concept model of PRATUSH is currently being built to present to the ISRO review committee in the coming months.

[Mayuri S Rao, Saurabh Singh, Jishnu Nambissan and members of the CMB DISTORTIONS lab]

PRATUSH-C3

Probing Reionization of the Universe using Signal from Hydrogen on Chandrayaan-3, was proposed as a custom designed precision spectral-radiometer to measure the low-frequency radio sky over 55-110 MHz

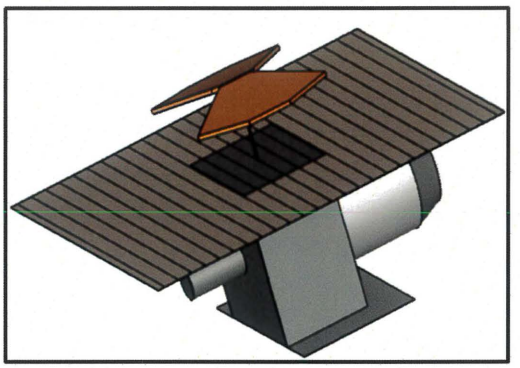


Figure 2. PRATUSH C3 design. A dipole antenna with a mesh reflector on the Chandrayaan-3 propulsion module (courtesy Kavitha K, A Raghunathan, PRATUSH-C3 team)

with an aim to detect the redshifted 21-cm signal from the Cosmic Dawn (CD). PRATUSH-C3 aimed to achieve the sensitivity required to detect this faint and information rich cosmological signal by operating in the radio quiet environment in the far side of the moon

occulted from Earth- and Sun-shine. Over four months spanning Feb-May 2020, PRATUSH efforts were focussed on developing a payload that could be accommodated within the technical and schedule constraints of the Chandrayaan-3 mission. Tremendous progress was made jointly by RRI and SAC teams towards designing and optimizing the payload concept. The PRATUSH-C3 experience has provided valuable lessons towards designing PRATUSH as a payload for a future mission, with the most valuable resource coming in the form of tight-knit interactions between RRI and ISRO (SAC) teams. The stringent constraints on power, mass, volume, of the payload imposed by the already mature design of the Chandrayaan-3 Propulsion Module were found to be in contradiction to those driven by the science requirements of PRATUSH-C3.

Mayuri S Rao led the PRATUSH-C3 activities, jointly with Saurabh Singh and Jishnu Nambissan T. This included writing the proposal for the experiment, developing the science case, system design, interaction with ISRO and RRI team members to develop, design, the experiment and implement some hardware capabilities, and preparation of technical reports.

[Mayuri S Rao, Saurabh Singh, Jishnu Nambissan and members of the CMB DISTORTIONS lab]

SARAS upgrades

SARAS-3 is the third in the line of SARAS (Shaped Antenna Measurement of background RAdio Spectrum) series of experiments. SARAS is a ground based experiment, and is a mature counterpart to PRATUSH, with the science goal of detecting the redshifted global 21cm signal from the Cosmic Dawn and Epoch of Reionization.

Based on the last science deployment, Mayuri S Rao has been leading the efforts to further enhance the system stability for improving the experiment sensitivity to signal detection. These include identifying sources of systematics in the measured spectrum on the field, which have not previously been seen in lab conditions, as well as making improvements to the system for the

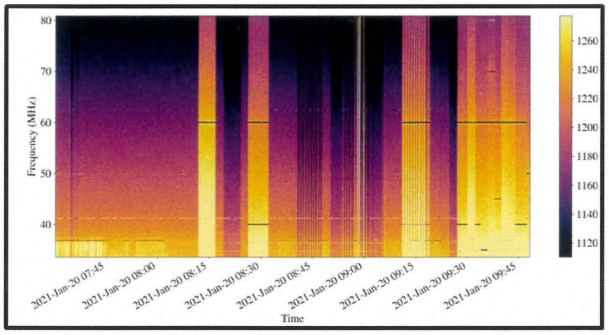


Figure 3. Sample waterfall plot of 2 hour observation of the SARAS-3 system with intentional tone injection to study the effect of power levels on RFI in the field on the measured spectrum.

next version of SARAS, namely SARAS-4. Working closely with group members, Mayuri S Rao has been running tests of the SARAS-3 system to simulate sky-observations as would be measured in the field as well as studying the effects of design changes on the instrument properties via data analysis of long lab observations.

[Mayuri S Rao and members of CMB DISTORTIONS lab]

SKA monitoring calibration and control system

The Square Kilometre Array (https://india.skatelescope.org/) is a multinational megascience project, of which India is a member. It is an upcoming radio telescope with SKA low spanning frequencies 50-350 MHz and SKA mid spanning frequencies 350 MHz - 14 GHz. SKA low will be located in Western Australia and SKA mid in South Africa. The key science goals of the SKA include (1) Galaxy evolution, cosmology and dark energy (2) Strong-field tests of gravity using pulsars and black holes (3) The origin and evolution of cosmic magnetism (4) Probing the Cosmic Dawn (5) The cradle of life and (6) Flexible design to enable exploration of the unknown.

SKA-low comprises an aperture array, it is expected to comprise 262,144 antennas in tiles of 16 antennas forming a total of 1024 stations. These stations are spread with a maximum baseline of 45 km, with 95 % of

the antennas in a core of radius 4 km. The backend digital electronics in the form of Tile Processing Modules (TPMs) enable beamforming effectively being able to realize commensal multi-frequency observations, by slicing up the telescope into sub-arrays each of which can operate with an independent scheduling block.

The monitoring, control, and calibration of the SKA-low telescope is thus a complex activity. Mayuri S Rao is a member of the SKA MCCS (monitoring, control, and calibration system) team. As an astronomer with an engineering background she plays the role of a deputy Product Owner on the Agile train of the software dominant MCCS team. She has in the past year worked with MCCS team members to provide clarity on the architecture of SKA-Low and is currently leading the program objective of designing an engineer user interface to most effectively engage the user of the SKA-MCCS functionalities. This activity has resulted in collaboration with members across the SKA low community, including the early users of MCCS. These are the verification and integration engineers as well as members at the Institute. RRI is expected to be leading the SKA low digital activities in India. With TPMs arriving at RRI shortly, the MCCS implementation and integration with TPMs will form a milestone not just for RRI, but SKA wide.

[Mayuri S Rao, T Prabu, Shiv Sethi along with members of the SKA MCCS (Monitoring Control Calibration System team) and Yashwant Gupta (NCRA)]

Readout technology for Cosmic Microwave Background telescopes

The sensitivity requirements of upcoming and future Cosmic Microwave Background experiments can be largely increased by increasing the number of photon-noise limited detectors (typically transition edge sensor bolometers). Deploying O(1,000-10,000) or more detectors in the receiver focal plane pose thermal, electrical, and noise challenges to detector readout technology. A promising upcoming readout technology for quantum noise limited detectors is the microwave SQUID multiplexer (mu-MUX) which combines the advantages of high multiplex-ability of microwave Kinetic Inductance detectors (MKIDs) and the legacy of field demonstrated TES-detectors. Efforts are ongoing to study and improve the noise performance of mu-MUX for CMB telescopes and quantum detectors with applications to quantum computing. This spans from cold-readout technology with designing and fabricating of low-loss superconducting Niobium

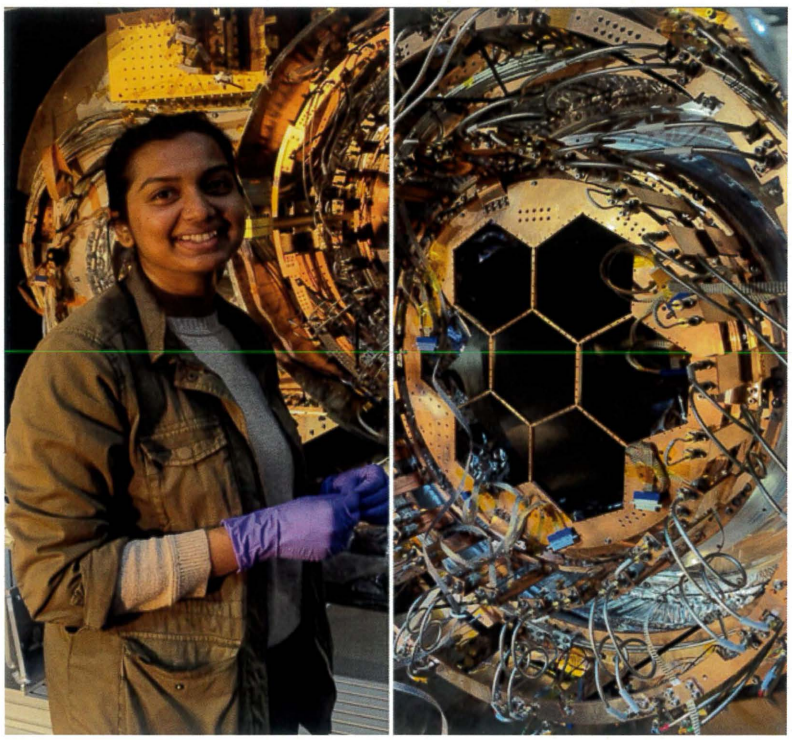


Figure 4. Installation of the Cold Readout Assembly into the Small Aperture Telescope 1 (SAT1) of the Simons Observatory. (Courtesy - Simons Observatory, not for circulation)

microstripline gigahertz resonators, effective RF wiring with cryogenic linear low-noise amplification of resonator signals and high performance FPGA based firmware development for tone-tracked resonator detection algorithms. The Simons Observatory (SO) is an upcoming polarization-sensitive Cosmic Microwave Background (CMB) experiment which adopts mu-MUX readout technology to read signals from O(10,000) detectors in the 3 small aperture telescopes and one large aperture telescope. SO will deploy in a site in the Atacama desert in Chile. The CMB-S4 is the stage 4 next generation CMB telescope that will deploy O(500,000) background limited detectors to reach the highest targeted sensitivity to CMB polarization. mu-MUX is a contending readout technology in addition to time domain multiplexing (TDM), and frequency division multiplexing (DfMUX), for CMB-S4.

Mayuri S Rao worked on developing the RF readout chain for Simons observatory mu-MUX readout and implementing the cold-readout-assembly (CRA) for the first Small Aperture Telescope (SAT1) of SO. This included mechanical, cryogenic, electrical, RF design, building, testing, and integration of the CRA with SAT1. SAT1 is expected to see first light in 2022 in Chile. She is an associate member of SO, and a part of the Galactic Science working group. The experience of designing complex cryogenic RF receivers will directly translate to planned activities of realizing APSERa (Array of Precision Spectrometers for the Epoch of Recombination) at RRI in the coming years.

[Mayuri S Rao, Simons Observatory collaboration (https://simonsobservatory.org/), with strong collaboration with Akito Kusaka (affiliation : Berkeley Lab, University of Tokyo)]

Detection of global 21cm signal using short spacing interferometers

Interferometers of sufficiently short spacing (of the order of a wavelength at relevant frequencies) have been proposed as an alternative to single antenna experiments to detect the global 21-cm signal. Such an interferometer is expected to have a response to the sky including any monopole component, while adding minimal instrument noise apart from the mutually coupled noise in the interferometers at short spacings. In order to investigate this approach, Jishnu Nambissan, along with collaborators at Curtin, built and deployed a short spacing interferometer at the Murchison Radio Observatory (MRO) in Western Australia. This instrument, named SITARA, has been acquiring data since March 14th, 2021. Current efforts are towards calibration and reduction of the acquired data.

[Jishnu Nambissan and members of the Curtin EoR group]

X-ray polarimeter (POLIX)

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

Development of the Qualification Model (QM) of the X-ray Polarimeter instrument POLIX has been completed and significant progress has been made towards completion of the Flight Model (FM).

- Some reworks were carried out on the QM detectors of POLIX. The QM, including one working detector module and all other mechanical components were assembled and was subjected to vibration at Qualification Level at URSC, IRSO. The vibration tests were successful.

- Assembly and tests were done for three out of four FM detectors of POLIX after reworks on some of the wire frames. Leak tests have been carried out successfully on the detector housings.

- All PCBs of two Backend Electronics (BE) for the QM have been made and tested.

- Two BE packages for the QM have been assembled and tested successfully with the detectors and ground checkout system.

- The BE QM packages have been successfully subjected to Qualification Level vibration tests at URSC-ISRO.

- Significant progress has been made in assembly of the Backend Electronics PCBs for the Flight Model of POLIX.

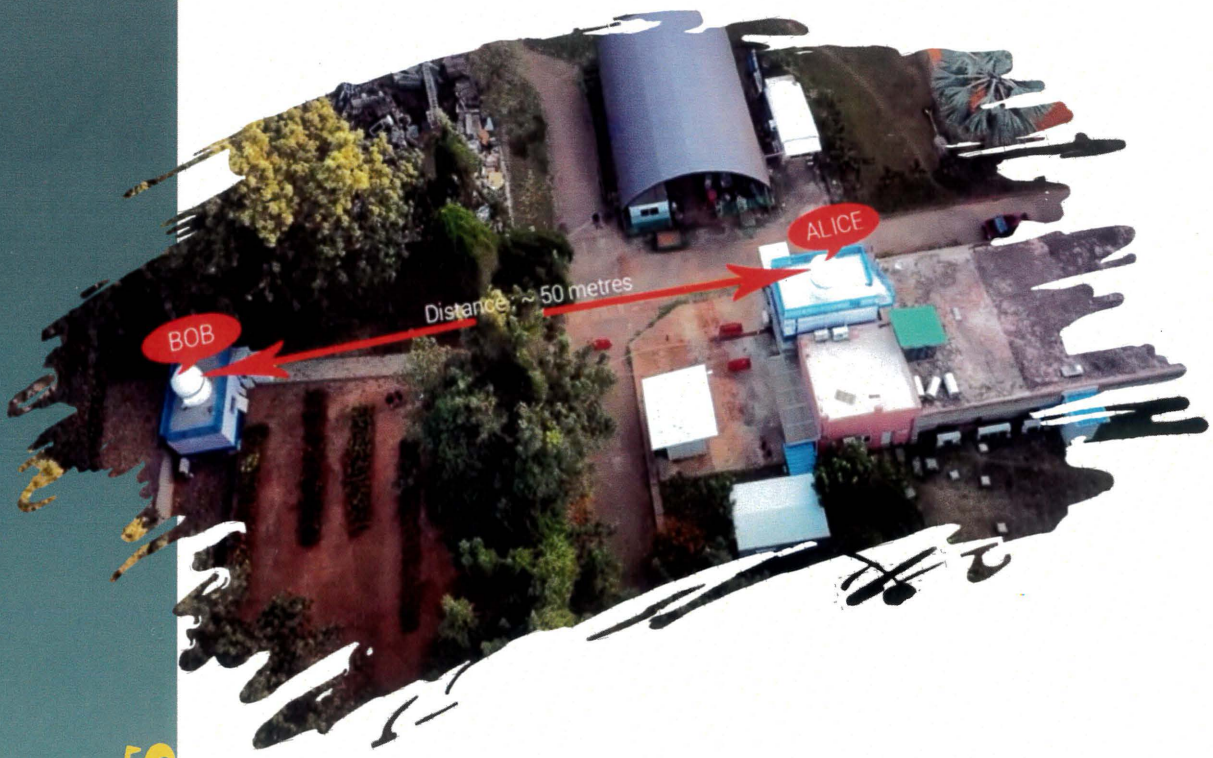
[Biswajit Paul, P V Rishin, Vikram Rana, M R Golapakrishna, S Krishnamurthy, Md Ibrahim, M Hemant, Pooja Verma, Md. Irshad, Harikrishna Sahoo, G. Rajagopala, Nandini Sreeanand, T S Mamatha, P Sandhya, Ketan Rikame and many members of Mechanical Engineering Services have made major contributions to all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

X-ray optics

X-ray optics utilizes grazing incident of X-ray photons onto a conical mirror that is coated with thin layers of highly reflective material (Gold, Pt, W, Si etc.) and thereby focuses X-rays to a focal point. Focusing of hard X-rays have been extremely challenging task as the angle of incidence decrease with increase in the energy of photons. Focusing capability for hard X-rays (beyond 10 keV) has tremendous potential to open a new discovery window in high energy astronomy. Fabrication of such hard X-ray telescope is a very ambitious project and hence requires active collaboration with several national institutions. A collaborative effort has been initiated between RRI, PRL Ahmedabad and URSC, ISRO to develop technology for hard X-ray telescope. Vikram Rana is leading the RRI part where they will develop a novel technique for the precise assembly of thousands of segmented X-ray mirrors that will mostly decide on the scientific performance of the telescope. During the past year, several tests on the automated epoxy dispense machine were carried out. Individual samples (mirror segments) containing a single glass sheet and graphite spacers bonded with epoxy were produced using this system. Next, this system will be utilised to stack these individual glass mirror segments using graphite spacers. A formal proposal has been submitted to ISRO (in collaboration with PRL and ISRO) for hard X-ray optics technology development to use with future X-ray missions.

[Vikram Rana]

light & 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, condensed matter, and ultracold and exotic states of matter. The underlying theme of these studies is to unravel fundamental processes which will qualitatively improve our understanding of the studied phenomena and provide new guiding principles. The knowledge thus gained will help in utilization of these principles both at the fundamental and at the applied level.

Focus 2020-21

Ultracold Atoms, Molecules and Ions Research

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

Collisions and Interactions

Modelling ultracold lithium ion-atom collision

Accurate estimation of the scattering properties at ultracold temperatures is challenging due to the demand for the precise knowledge of interactions between the colliding partners. Sadiq Rangwala and his group members Amrendra Pandey, Niranjan Myneni and Nishant Joshi along with collaborator Olivier Dulieuhave identified the aspects of interactions that play the defining roles in the scattering calculations. They also computed potential energy curves for the $^7Li^+$-^7Li, $X^2\Sigma_g^+$ and $A^2\Sigma_u^+$, and determined their collisional properties.

[A Pandey, M Niranjan, N Joshi, S A Rangwala and O Dulieu (Lab. Aimé Cotton, CNRS, France)]

Measurement of collisions between laser-cooled cesium atoms and trapped cesium ions

During the past year Sadiq Rangwala along with collaborator Sourav Dutta reported the measurement of collision rate coefficient for collisions between ultracold Cs atoms and low-energy Cs^+ ions. The experiments were performed in a hybrid trap consisting of a magneto-optical trap (MOT) for Cs atoms and a Paul trap for Cs^+ ions. The ion-atom collisions impart kinetic energy to the ultracold Cs atoms, resulting in their escape from the shallow MOT and, therefore, in a reduction in the number of Cs atoms in the MOT. By monitoring, using fluorescence measurements, the Cs atom number, and the MOT loading dynamics and then fitting the data to a rate equation model, the ion-atom collision rate was derived. The Cs–Cs^+ collision rate coefficient $9.3(\pm0.4)(\pm1.2)(\pm3.5)\times10^{-4}m^3s^{-1}$, measured for an ion distribution with most probable collision energy of 95 meV (≈kB1100K), was found to be in fair agreement with theoretical calculations. As an intermediate step, the photoionization cross section of Cs $6P_{3/2}$ atoms at 473 nm wavelength was also determined to be $2.28(\pm0.33)\times10^{-21}m^2$.

[Sadiq Rangwala and Sourav Dutta(TIFR, Mumbai)]

Analysis of multipolarlinear Paul traps for ion–atom ultracold collision experiments

Sadiq Rangwala and his students Niranjan Myneni and Anand Prakash evaluated the performance of multipole, linear Paul traps for the purpose of studying cold ion–atom collisions. A combination of numerical simulations and analysis based on the virial theorem was used to draw conclusions on the differences that result, by considering the trapping details of several multipole trap types. Starting with an analysis of how a low energy collision takes place between a fully compensated, ultracold trapped ion and an stationary atom, they have shown that a higher order multipole trap is, in principle, advantageous in terms of collisional heating. The virial analysis of multipole traps, along with the computation of trapped ion trajectories in the quadrupole, hexapole, octopole and do-decapole radio frequency trap was also part of this study. They undertook a detailed analysis of the motion of trapped ions as a function of the amplitude, phase and stability of the ion's motion to evaluate the experimental prospects for such traps. The present analysis has the virtue of providing definitive answers for the merits of the various configurations, using first principles.

[Niranjan Myneni, Anand Prakash and Sadiq Rangwala]

Quantum Simulation of Condensed Matter Physics using Degenerate Gases

Status of the experimental facility to study quantum degenerate mixture of neutral sodium and potassium atoms

During 2020-2021,Saptarishi Chaudhuri and group members Sagar Sutradhar, Subhajit Bhar, Shreya Bagchi, Bidyut Bikash Boruah and Sanjukta Roy have completed the installation of the ultra-high vacuum system of the state-of-the-art Quantum Mixture experiment. These experiments have the long-term goal of investigating the emerging physics of quantum degenerate mixtures and polar molecules with tunable, long-range dipolar interactions to simulate complex condensed matter phenomena. The experiment facility is capable of simultaneously cooling neutral Sodium (23Na) and Potassium (Both 39K and 40K) to nano-Kelvin temperatures via laser cooling and evaporative cooling techniques. The vacuum system consists of two high-flux sources of cold atomic beam in the form of two- dimensional magneto optical trap for both species of atoms. Atoms from the sources will be captured in a dual-species magneto optical trap (MOT) simultaneously. A magnetic transport stage was designed to simultaneously transport the trapped atoms in a moving magnetic trap over a distance of nearly a meter to a connected glass vacuum cell with large optical access and ultra-high vacuum. The photograph of the installed vacuum system is presented in Figure. 1. Most of the vacuum components were either purchased or machined in RRI mechanical workshop. Ultra-high vacuum glass cells were designed in-house and manufactured by an external vendor. The lasers for trapping and cooling of atoms and corresponding high resolution spectroscopy set-ups were completed during this year and optimized. In Figure 2, some of the optical, optomechanical and spectroscopy components installed in the laboratory is shown.

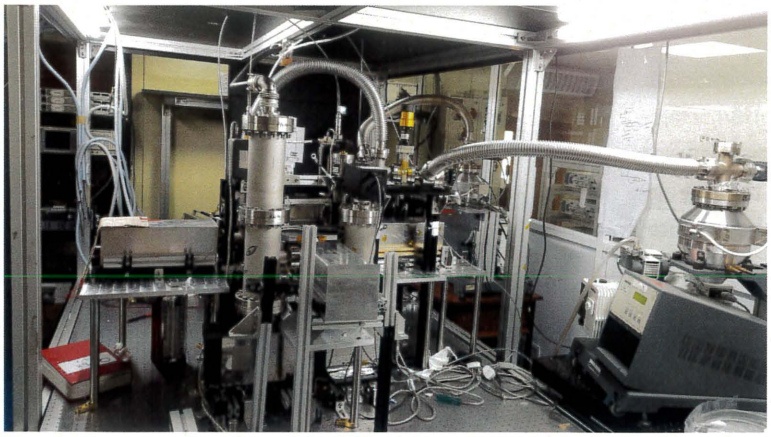


Figure 1. The ultra-high vacuum system installed in Quantum Mixtures laboratory.

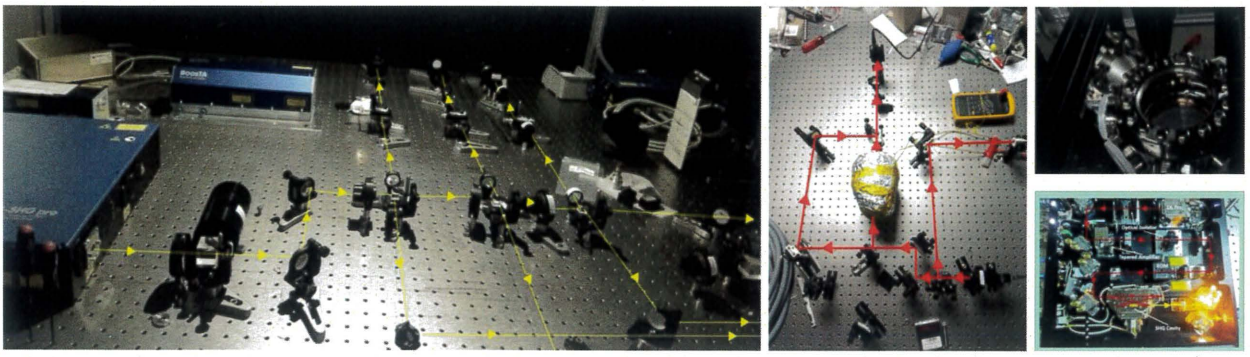


Figure 2. A collage of photos showing the installed optical, optomechanical components and high resolution spectroscopy set-ups for laser cooling and trapping of Sodium and Potassium atoms.

Measurements of response function of cold atoms in magneto optical trap

Subhajit Bhar, Maheswar Swar, Supurna Sinha, Sanjukta Roy and Saptarishi Chaudhuri along with collaborators Urbashi Satpathi and Rafael Sorkinhave completed a set of experiments to study the response function of cold atoms in a magneto optical trap (MOT) subjected to sudden mechanical impulse. Displacement of the cloud of cold atoms in a magneto optical trap using an external uniform magnetic bias field followed by sudden switching off of the external field and observations of the motion of the cloud (The schematic of the experimental set-up is provided in figure 3) enabled them to extract the response function of the ultra-cold atoms from their measurements. A typical centroid motion of the atomic cloud as a function of time is shown in figure 4. In a related set of experiments, the cloud of ultra-cold atoms was allowed to diffuse in the presence of optical potential and the diffusion rate was measured by direct imaging of the atomic cloud. These measurements are the first steps towards measuring the quantum diffusion experimentally. These measurements provide insights into fundamental physical processes involved in laser cooling and trapping and the applicability of Quantum Langevin Equation (QLE) in cold atom experiments. A manuscript with the experimental and theoretical results is now complete and a pre-print is available on Arxiv.

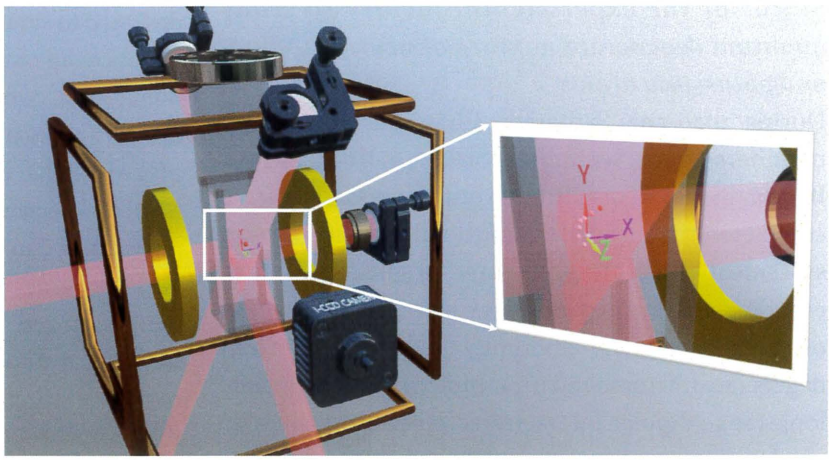


Figure 3. The experimental set-up to study the response function of cold atoms

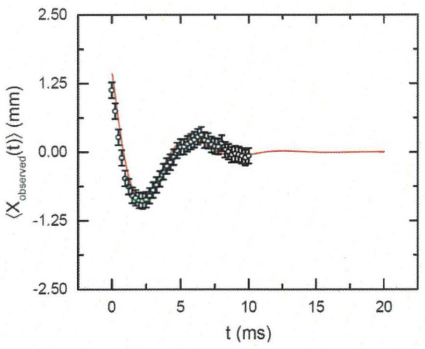


Figure 4. A typical motion of the cold atomic cloud. The relative displacement (ΔY) is the difference between the mean position of the cold cloud with and without bias field.

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

Precision Atom-Light Interaction and Spectroscopy

Unravelling the mechanism behind the phase-dependent amplification of an optical field controlled by a microwave field.

For the past 3-4 years Andal Narayanan and her students Adwaith K V, Pradosh K N and Saaswath J K along with collaborator Fabien Bretenaker have been experimentally studying an atom-light interaction scheme which creates strong superposition of internal states of atoms called the dark state using external electromagnetic field variables. In the Quantum Optics lab, microwaves and optical fields were used to achieve this dark state. A schematic of the atomic sample inside a microwave cavity and interacting with microwave and optical fields is shown in Figure 5(b). This particular atomic system connects two optical and one microwave field through a relay-like cyclic closed interaction that creates a dark superposition state of its ground and metastable state. They found that in this atom-light system, using the phase of microwave field the transmission and absorption properties of the optical probe field can be controlled. Using a hybrid (electric and magnetic) field induced three-wave mixing nonlinearity in these systems, they have realised in the past few years, a fast, high-contrast optical switch controllable by the phase of a microwave field, generation of a new optical field through microwave-optical induced non-linear interaction and microwave phase dependent amplification of the optical probe field.

Efforts during the past year has led to the unravelling of the physical mechanism behind the amplification phenomenon to be an interference effect between the microwave field and the coupling optical field mediated by this dark state. The critical parameter identified by this model is the so-called two-photon detuning parameter which decides the existence of the dark state. The theoretical model (continuous curve) was found to fit the experimental data points for high and low gain (Figure 5. b) with very good accuracy. The resultant visibility curve (Figure 6.) which shows the contrast between high and low optical field gain values as a function of intensity of microwave field also closely followed the theoretical prediction as shown below. This work is now published: *OSA Continuum 4(2), 702–710 (2021).*

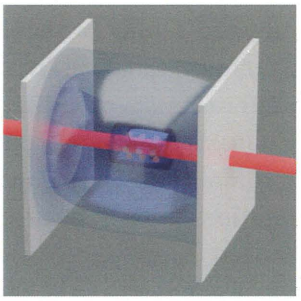


Figure 5. (a) Schematic representation of atoms inside a microwave cavity interacting with microwaves and optical laser fields depicted in red.

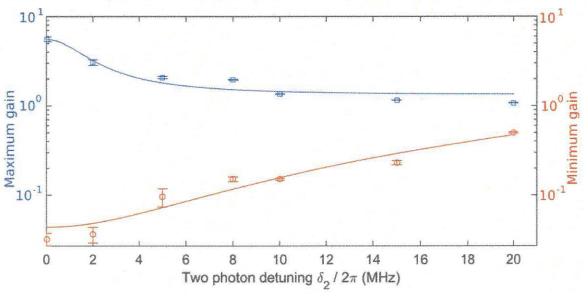


Figure 5. (b) The theoretical model (continuous curve) and the experimental data points for high and low gain.

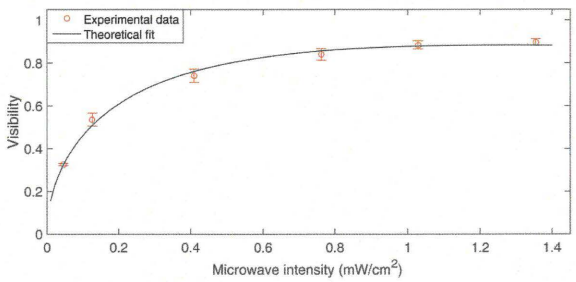


Figure 6. Visibility curve showing the contrast between the high and low gain optical values based on the theoretical model (continuous curve) and the experimental data points.

[Adwaith K V, Pradosh K N, Saaswath J K and Andal Narayanan along with collaborator Fabien Bretenaker(Adjunct Professor, RRI and University of Paris-Saclay, France)]

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

It is well known that a group delay of a given light pulse travelling in a material medium can be modified through its non-linear interaction with other control fields .It has been found that the group velocity and group delay control of electromagnetic (EM) pulses in atomic gaseous media can be controlled through the phenomenon of electromagentically induced transparency (EIT). Using EIT one can eliminate linear response of the atomic medium to specific light frequencies and use low-light intensity induced non-linear responses to effect subluminal (slow) and superluminal (fast) propagation of an EM pulse. Importantly it was shown that using phase and intensity parameters of a control microwave field, the group delay of an optical pulse can be manipulated. All the group delay control studies done so far relied on the density of the atomic sample to effect a measurable delay or advancement. For lower densities the delay (or advancement) was insignificant. In a recent theoretical study, Andal Narayanan and her students Saaswath J K, Adwaith K V, Pradosh K N, along with collaborators Fabien Bretenaker and Barry Sandershave shown that a significant density independent control of group delay of a non-linearly generated optical pulse can be produced in their system. Specifically, using a novel three wave mixing non-linearity in their atomic system they have shown that the propagation of a generated optical pulse from subluminal to superluminal can be controlled by changing the parameters of a frequency separated microwave drive field (see Figure 7). This work has resulted in a publication *DOI: 10.1364/OE.424110(2021).*

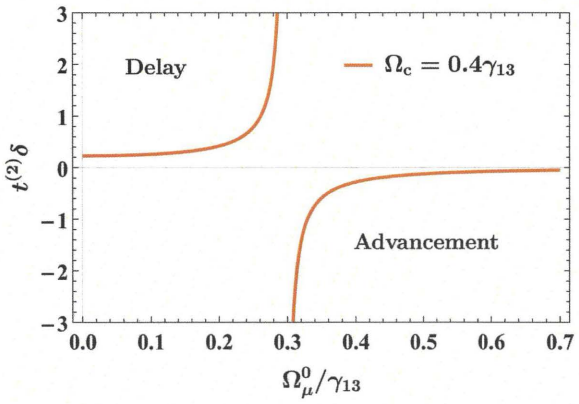


Figure 7. Group delay as a function of intensity of control microwave field.

[Saaswath J K, Adwaith K V, Pradosh K N and Andal Narayanan along with collaborators Fabien Bretenaker (Adjunct Professor, RRI and University of Paris-Saclay, France) and Barry Sanders (University of Calgary, Canada)]

Digital communication using an atomic radio-over-fibre device

In the past few years, there has been a steady progress in utilising cyclic and closed atomic level schemes such as those Pradosh K N, Adwaith K V, Meena M S and Andal Narayanan have been working with (Figure 8) to interface microwave with optical frequencies in a coherent and phase dependent manner. The EIT effect has been utilized to effect such an interface. One interesting off-shoot of such studies has been in the field of communication. For example audio modulation of a microwave carrier and its optical read-out has been recently demonstrated by making these disparate frequencies talk to each other through non-linear mixing mediated by the atoms. However a practical implementation of an established digital communication protocol with a cyclic atomic system has not been demonstrated until now.

Recent research efforts by Pradosh K N, Adwaith K V, Meena M S and Andal Narayanan has been towards demonstrating two digital phase modulation schemes connecting microwave and optical frequencies using an atomic radio-over-fibre device. They have demonstrated a binary phase-shift keying (BPSK) and a customised 4 phase-shift keying (C-4PSK) protocols. Signals were encoded in phase changes of a ~3 GHz microwave carrier. Through the cyclic and closed interaction of microwave with other optical fields mediated by the atoms (see Figure 8) these microwave phase modulations were coherently imprinted as optical intensity changes. The optical demodulation readout was demonstrated at 795 nm. They have also

demonstrated a viable signal bandwidth of about 1 MHz and a carrier frequency change of about ~15 MHz.More importantly, their atomic system amplifies the demodulated optical signal through a hybrid second-order nonlinearity induced in the atoms involving a magnetic dipole and an electric dipole transition. This amplification increases the contrast of the output optical signal and makes it sensitive to small input phase changes. Furthermore their system utilises for its communication protocol, a dark state which is also a quantum memory state making this scheme ideal for storage of microwave quantum signals and its coherent conversion to optical regimes. This experiment is one of the very few direct digital phase modulation and demodulation schemes to be implemented in an amplifying atomic radio-over-fibre device. Shown in Figure 9 are explicit demonstration of input microwave phase changes to output optical intensity changes for BPSK and C-4PSK protocols.

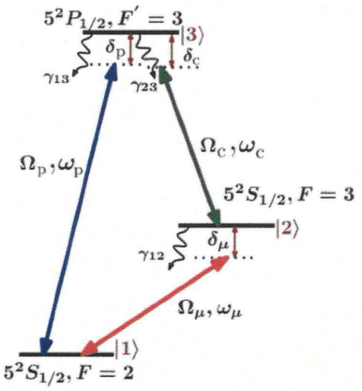


Figure 8. Atomic level scheme used for implementation of digital communication protocol. Signals are embedded in the phase of the microwave field (red) and retrieved coherently as intensity changes in the optical (blue).

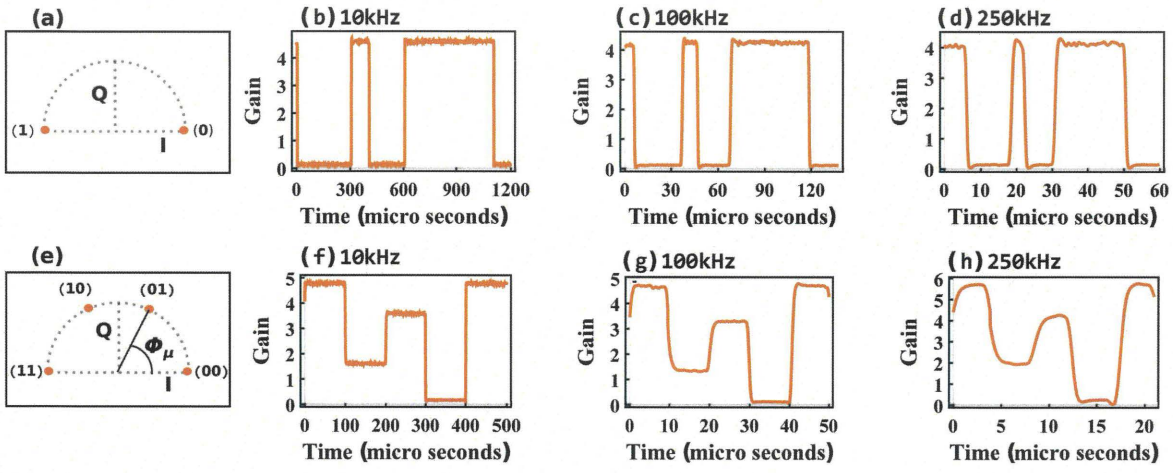


Figure 9. For input microwave phase change protocols depicted in (a) and (e) for BPSK and C-4PSK respectively the output optical intensity changes shown for various input signal frequencies in (b, c, d) and (f,g,h).

Spin correlations in Raman pumped cold rubidium atoms

Maheswar Swar, Dibyendu Roy, Subhajit Bhar, Sanjukta Roy and Saptarishi Chaudhuri have, during the past year, completed the work on measuring the spin correlations from neutral cold atoms. This is the first measurement of spin correlations in cold atoms using Faraday rotation fluctuation technique. They successfully measured Faraday rotation fluctuation in an ensemble of cold atoms coherently driven by a pair of Raman laser beams, cooled down to 150 micro-Kelvin. The highlight of their previous published research work has been the demonstration of high precision magnetometry using spin noise measurements and non-perturbative detection of atomic magnetometry precision by two orders of magnitude. This current work has demonstrated the potential of using this technique to measure quantum correlations. The magnetometry related article has been published in *IEEE Transactions on Instrumentation and Measurements*. Figure 10 shows one of the highlights of the work, namely the time resolved high resolution measurement of the external magnetic field using this technique.

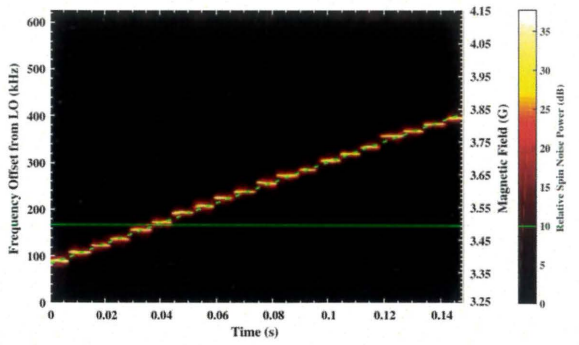


Figure 10. Time resolved high resolution magnetometry using spin correlation spectroscopy

In experiments to study the spin correlations in cold atoms, ^{85}Rb atoms were trapped and cooled inside a vacuum chamber by means of magneto- optical trap (MOT). In previous experimental set-up where spin correlation from the thermal atoms were detected, a far off resonant linearly polarized probe laser beam was passed through the atomic sample and the polarization fluctuation (or the fluctuation of the Faraday rotation) of the probe beam was measured. In the new set-up a pair of Raman laser beams were added to coherently drive the atoms between the magnetic sub-states. The schematic diagram describing the experimental set-up is shown in Figure 11.

Figure 12 demonstrates the extraction of spin correlation signal from the cold atoms as well as the measurement of their intrinsic spin relaxation lifetime. A comprehensive theoretical description of the result based on Optical Bloch Equations (OBE) has been developed. The manuscript has been submitted to *Physical Review Letters*. Another noteworthy recent result is the observation of inter-species spin-exchange collision using spin correlation measurements. This set of measurements were done in a thermal atomic vapor at room temperature. The vapor cell contained both isotopes of Rubidium atoms and the Raman lasers were used to drive the coherent spin oscillations in ^{85}Rb isotope and measure the spin correlation of ^{87}Rb isotope. The experimental data is presented in Figure 13, where one can see that resonant spin excitation in ^{85}Rb can be read via spin correlation spectroscopy technique in ^{87}Rb.

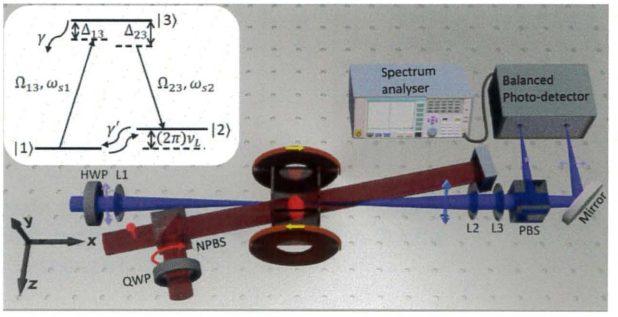


Figure 11. Schematic of in-situ spin correlations measurement using cold atoms. This cloud has been coherently driven by Raman beams during the experiment.

The resonant spin exchange transferred the spin excitation from one species to another. This is one of the first direct detection of spin exchange collisions in atomic systems.

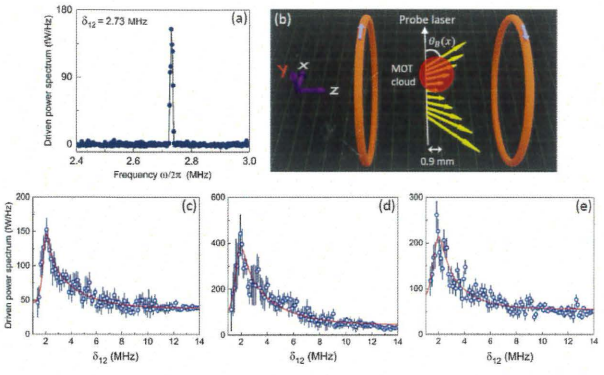


Figure 12. Observation of spin coherences via Faraday rotation fluctuation measurements in cold atoms.

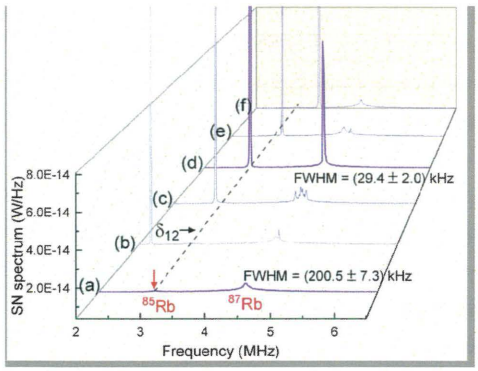


Figure 13. Direct detection of spin exchange collisions via spin correlation spectroscopy in Rubidium atoms.

[Maheswar Swar, Dibyendu Roy, Subhajit Bhar, Sanjukta Roy and Saptarishi Chaudhuri]

High resolution Rydberg spectroscopy and single atom traps

An experimental project on trapping and cooling of single atoms and performing high resolution optical spectroscopy of Rydberg atoms was undertaken during the past year by Sanjukta Roy, Shovan Kanti Barik, Silpa B S, and Saptarishi Chaudhuri. The Magneto Optical Trap (MOT) of neutral Rubidium atoms was optimized during the past year and high lifetime over several tens of seconds was observed. They were able to trap, cool and detect as low as 30 atoms using home built APD based high resolution detectors. High resolution spectroscopy using electromagnetically induced transparency (EIT) in ladder system is being undertaken to measure the absolute transition frequencies of fine structure states with high principal quantum number. These experiments on Rydberg atoms open up the possibilities of performing Quantum Logic Gate operations in cold atoms making them useful systems for Quantum information processing and quantum computations.

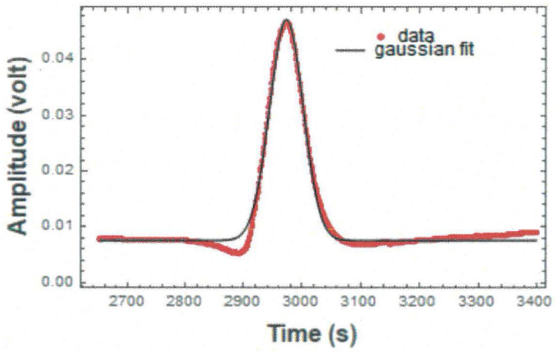


Figure 14. Rydberg EIT signal corresponding to transition into $45D_{3/2}$ fine structure state.

[Sanjukta Roy, Shovan Kanti Barik, Silpa B S and Saptarishi Chaudhuri]

Intense Light-Matter Interactions

The nature of the interaction between a powerful laser pulse and a material medium depends on the laser characteristics (fluence, pulse duration, wavelength, beam quality) and material composition. At moderate light intensities (perturbative regime) nonlinear optical phenomena will become evident. At higher light intensities close to the threshold of material ablation, laser-induced periodic surface structuring (LIPSS) can be carried out on suitable solids, to fabricate diverse micron and sub-micron scale surface features. At still higher intensities a plasma plume will be formed on the target, which can be investigated using optical and electrical diagnostic techniques. During the past year, members of Reji Philip's Ultrafast and Nonlinear Optics lab at RRI and collaborators investigated nonlinear absorption exhibited by certain novel materials, laser-induced micro and nanoscale pattering of silicon surfaces, and laser-produced plasmas generated in a thin nickel film in the rear ablation geometry.

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

Nonlinear optical devices have various technological applications. One such device is the optical limiter, which protects sensitive optical detectors and human eyes from potential damage due to accidental exposure to intense laser beams. Optical limiters work mostly on the principle of nonlinear absorption, to keep the power transmitted by an optical system below some specified maximum value, regardless of the magnitude of the input. They maintain high transmittance at low input powers and low transmittance at high input powers. During the past year, members of the Ultrafast and Nonlinear Optics lab undertook nonlinear absorption measurements in various materials including the natural indigo dye, nitrochalcone derivatives, silver-decorated graphene oxide nanohybrids, alloy-nanoparticle embedded carbon nanotubes etc., using the Z-scan technique. The effective two-photon absorption coefficients of the materials were calculated from these measurements. Ten papers were published based on these studies. Results obtained indicate the potential of these materials for application as efficient optical limiters for the safety of human eyes and sensitive optical detectors from accidental exposure to harmful laser radiation.

[Reji Philip, Nithin Joy, Beryl C Das, Ajay Kumar and Nancy Verma from RRI, with collaborators B Sahoo (IISc, Bangalore), A Subashini (Bharathidasan University, Tiruchirapalli), V P Mahadevan Pillai (University of Kerala), N Kalarikkal (Mahatma Gandhi University), D. Sajan (Bishop Moore College) and B Anand (St. Joseph's College), who supplied the materials for investigation].

Laser-induced periodic surface nanostructuring of solids

Laser-induced periodic surface structuring (LIPSS) is a very successful technique for the fabrication of diverse surface patterns of micron and sub-micron scale features on solid surfaces. LIPSS patterns are formed when interference occurs between incident laser light and surface scattered electromagnetic waves (SEWs). Reji Philip, Nancy Verma and Nithin Joy, along with K K Anoop (CUSAT, Cochin), investigated the morphology and optical properties of surface structures fabricated on crystalline silicon by employing femtosecond and nanosecond laser pulses. The roles of laser parameters (pulse duration, wavelength, and polarization) and ambient pressure in the texturing process were studied. While 100 fs laser pulses led to the formation of nanoscale periodic and quasi-periodic patterns, 7 ns laser pulses generated random microscale patterns on the silicon surface. A substantial reduction of optical reflectivity was observed in the UV-Vis region due to surface blackening, which was more effective for texturing using 100 fs laser pulses. Raman spectroscopy revealed that the crystallinity of the silicon lattice was not affected by LIPSS patterning, and that nanosecond laser patterning resulted in a relatively higher scattering efficiency. Black silicon fabricated through fs-LIPSS with nanoscale periodic patterns is potentially useful

for numerous applications in photovoltaics, electro-optic devices and sensors. A manuscript based on this study has been prepared and communicated for publication.

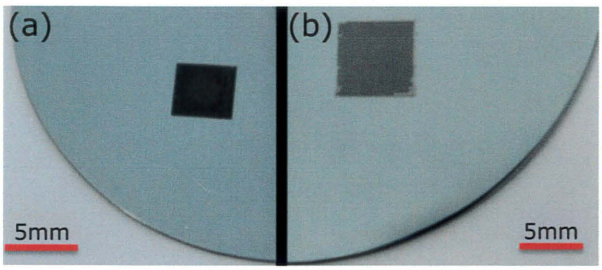


Figure15: Photographs of silicon wafers textured using (a) 100fs laser pulses and (b) 7 ns laser pulses. Blackening is higher for fs laser texturing [results to be published].

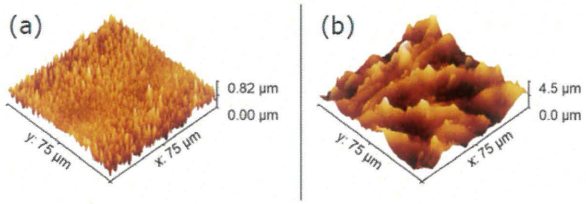


Figure16: 3D topography of (a) fs, and (b) ns laser texturedcrystalline Si surfaces, measured using an atomic force microscope [results to be published]. [Reji Philip, K K Anoop (CUSAT, Cochin)]

Laser produced plasmas (LPPs) from thin films

When a material target is irradiated by a powerful laser pulse, a plasma plume will be generated on the target under the right ambient conditions. Laser-produced plasmas (LPPs) have diverse applications, including pulsed laser deposition (PLD), nanoparticle generation, high harmonic generation (HHG) and EUV & X-ray production. Generating plasma from thin films in the rear ablation geometry is relatively less employed in LPP studies. Reji Philip, along with collaborators from IPR, Ahmedabad [J Thomas, H C Joshi, A Kumar, R Philip, *Phys. Rev. E102, 043205 (2020)*], produced LPPs in this geometry from a thin Ni film of 50 nm thickness coated on a quartz substrate. They undertook a detailed study of the acceleration of ions in the plume generated by nanosecond laser pulses, for varying background pressures and laser energies. The spectroscopic time of flight (STOF) spectra recorded for ionic transition clearly showed an enhancement in the velocity of the slow component as the background pressure was increased. In addition, a large asymmetric spectral broadening in the 712.22nm neutral line was observed, which increased with background pressure. While these observations are similar to some of the reported studies on the acceleration of ionic species through double-layer formation, the electric fields calculated from the measured acceleration are anomalously higher, and a double-layer concept is inadequate. The large asymmetry observed in the neutral line profile indicated the presence of microelectric fields inside the plasma plume, which is expected to play a role in the continuous acceleration of the ions. This asymmetry exhibited temporal and spatial dependence, indicating that significant electric field is present in the plasma plume even for longer durations and larger distances from the target. These spectroscopic observations of acceleration were complemented by triple Langmuir probe measurements. Such large ion accelerations for the relatively low laser intensities used in this experiment are hardly reported in literature so far.

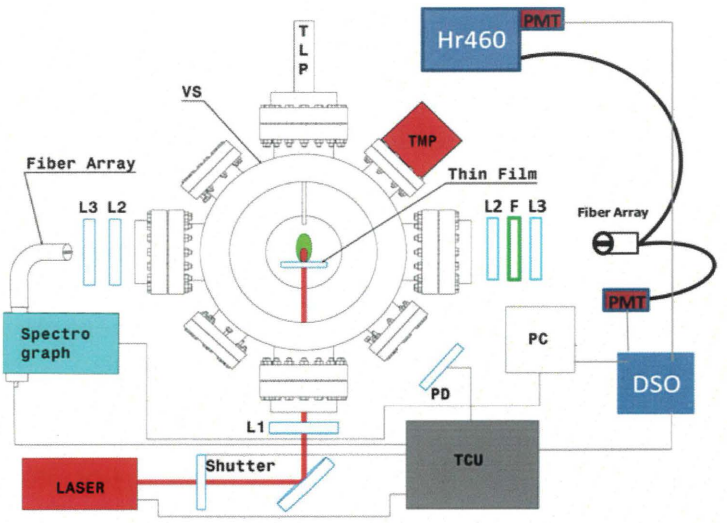


*Figure 17. Schematic diagram of experimental setup showing the arrangement of sample (thin film), triple Langmuir probe (TLP), and laser system aligned to the vacuum system (VS). TMP is the turbo molecular pump, L1 is the focusing lens, L2 and L3 are the lens system to image the plasma plume to fiber array. F is the band pass interference filter, Hr460 is the high-resolution spectrometer, PMT is the fast photomultiplier Tube, DSO is the fast digital storage oscilloscope, and TCU is the trigger and control unit which synchronizes the instruments with laser pulses. Data is acquired on a personal computer (PC). From Thomas et.al., Phys. Rev. E**102**, 043205 (2020).*

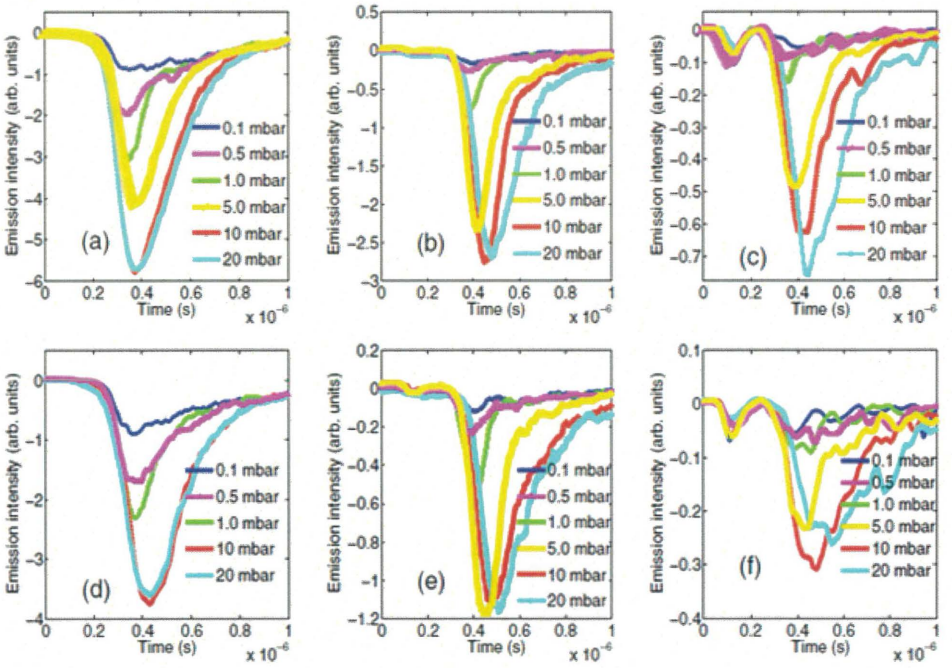


*Figure 18. Evolution of STOF spectrum of neutral lines 3 mm away from the sample for different background pressures and laser energies. 100 mJ (a)–(c) and 50 mJ (d)–(f) for10 ns, 1064 nm laser. The neutral lines are 361.94 nm (a), (d), 508.11nm (b), (e), and 712.22 nm (c), (f). From Thomas et.al., Phys. Rev. E**102**, 043205 (2020).*

[Reji Philip, Jinto Thomas (IPR, Ahmedabad)]

Quantum Communications, Quantum Optics and Quantum Information Science

Quantum Communications

The area of quantum communications is an exciting new area for the Indian community and RRI is playing a leading role in developments therein through several projects and research directions in this domain. This year was particularly noteworthy in these developments as not only did the Quantum Information and Computing lab publish India's first end to end free space quantum key distribution in-lab experiment in a prestigious international forum but also performed the first inter-building free space quantum communications experiment connecting two buildings at RRI through an atmospheric channel. These are very important milestones in the quest towards establishing indigenous satellite based secure quantum communications in India.

The currently prevalent means of secure communication is through classical cryptography. When the information to be communicated needs to be kept secure, for instance, in defence, banking and other such strategic sectors, the information is encoded by the sender in what is called a "key" which is then decoded by the receiver by using the key in their possession. The distribution of the key forms the basis of the security and one of the common techniques used is based on the algorithmic hardness of problems for instance the factorization problem. For instance, multiplying two numbers has a lower class of "hardness" in terms of algorithmic complexity than factorization of a number into its two prime factors. Factorization has long been used as the basis of security in public key distribution algorithms like the RSA algorithm. In what is called "Private Key" distribution, one still needs to rely on trusted human carriers. The imminent onset of small quantum registers jeopardizes the security of classical key distribution as they would be able to run what are called Shor's algorithm which can break the hardness of the factorization problem. What is needed is a "quantum" solution to the problem where the basis of the security are laws of nature and not mathematical hardness of problems or algorithmic complexity. This brings us to "Quantum Key Distribution" or QKD. QKD uses laws of quantum mechanics to ensure "absolute" security of key distribution.

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

Towards the project on "Quantum Experiments using Satellite Technology (QuEST)", QuIC lab has achieved several ground based milestones over the last year. This is an ambitious multi-year project to demonstrate free space quantum key distribution over different distance domains in varying environmental conditions. This project is in collaboration with the Indian Space Research Organization (ISRO) and will involve demonstrating quantum key distribution over large

distances using a satellite as a trusted node. This is India's first project in satellite based quantum communication and we are extremely excited by its prospects and look forward to reporting on different milestones in the years to come.

Rishab Chatterjee, Sourav Chatterjee, Satyaranjan Behera, A Nagalakshmi, Rakshita R M and the PI of the project, Urbasi Sinha have been the people involved in the project last year. V Mugundhan, R Somsekhar as well as A Raghunathan from EEG have been providing able technical consultancy in different capacities. More people are expected to join this project over the course of the next year.

The project started in January 2018 and the first year essentially saw the project being established on a firm footing in the lab with dedicated personnel being hired as well as dedicated equipment and resources being acquired. Sourav Chatterjee, A Nagalakshmi and A Anuradha joined the project in 2019. Along with consolidation and mobilisation, they have been productive scientifically. Last year, the B92 protocol was established in the lab with an average key rate of 46 Kbits/second and average QBER of 3.5% (bounded by the 4.2% information security threshold) over a ~2 metre free space distance (to the best of knowledge, these are better than any other reported numbers on this in existing literature). Details of the work on this project can be found at *http://www.rri.res.in/quic/* as well as *Phys. Rev. Applied 14, 024036 (2020).*

2020 year's progress: While an in lab version of the B92 protocol was demonstrated last year, 2020 saw the key rates improved further. One of the major accomplishments in this project this year was coming up with a much needed simulation toolkit, which is able to simulate end to end QKD protocol taking into account practical experimental imperfections. While there are a few commercially available toolkits, none of them seems to contain imperfections and practicalities associated on ground. This toolkit aims to bridge this very important gap. This work was published: *Phys. Rev. Applied 14, 024036 (2020).*The above manuscript, along with its attendant analysis, experimental results and algorithms was a major milestone in the ongoing QuEST project with ISRO. This is also India's first end to end free space QKD experiment that has been published in an international peer reviewed journal.

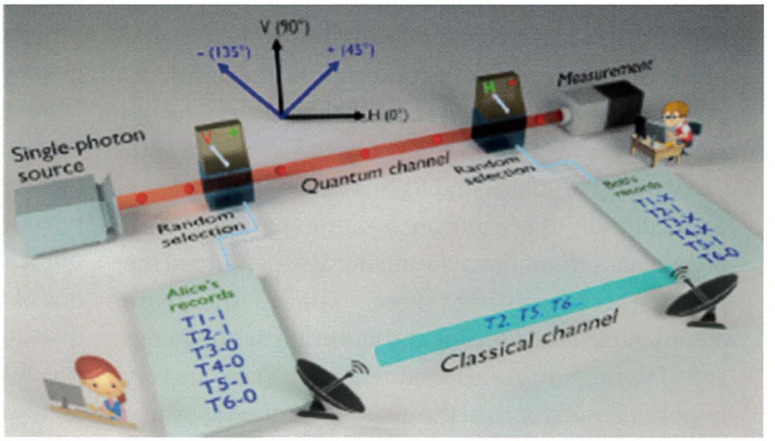


Figure 19. Schematic of the B92 experiment using polarization encoding [Phys. Rev. Applied 14, 024036 (2020)]

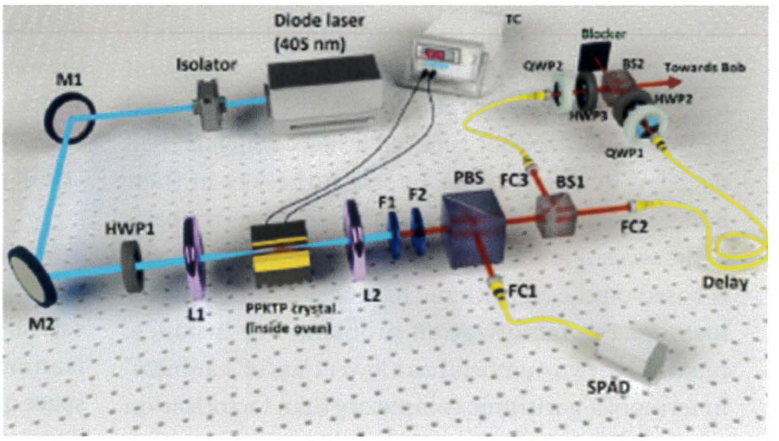


Figure 20. Schematic of the single photon source used in the experiment [Phys. Rev. Applied 14, 024036 (2020)]

In 2019, entanglement based quantum key distribution was demonstrated in the lab with reasonable key rates and QBER. As reported in last year's annual report, a dedicated entangled photon source was developed for the purpose (with an extremely high Concurrence of 0.99) and demonstrated BBM92 entanglement based QKD protocol in the lab. During the past year, the source was optimised further with much higher key rates and lower QBER than the initial demonstration. A manuscript is currently being written on these results. With this, QuIC lab is reportedly the first lab in India to have working experimental demonstrations of both "Prepare and Measure" type QKD as well as "entanglement based QKD".

The next major milestone towards satellite based QKD involves moving outside the lab and being able to demonstrate quantum key distribution over longer distances, through an open atmospheric channel.

A major part of 2020 was spent in developing both physics as well as engineering based requirements for free space QKD through an atmospheric channel. While in-lab QKD was already established, the free space involving an atmospheric channel brings in new challenges and myriad capacity building requirements. Covid-related lab closures as well as students going home during lockdown and then returning at different points of time, with attendant quarantine requirements, definitely led to severe hampering of lab work. In spite of this, the team was able to demonstrate India's first free space QKD experiment between two buildings at RRI in early 2021. This necessitated the development of dedicated telescope systems as well as stable mounts for the same, perfection in optical alignment using these systems along with beacon lasers, accurate time synchronisation systems using GPS as well as further optimisation of the entanglement properties of the source. A photo of the free space link where the "Alice" and "Bob" stations are clearly marked is shown in Figure 21.

Figure 21. The free space link between the "Alice" station at QuIC lab and the "Bob" station which is located in a portable ground station ~50 metres away. The entangled source i.e. "Charlie" is located within the lab.

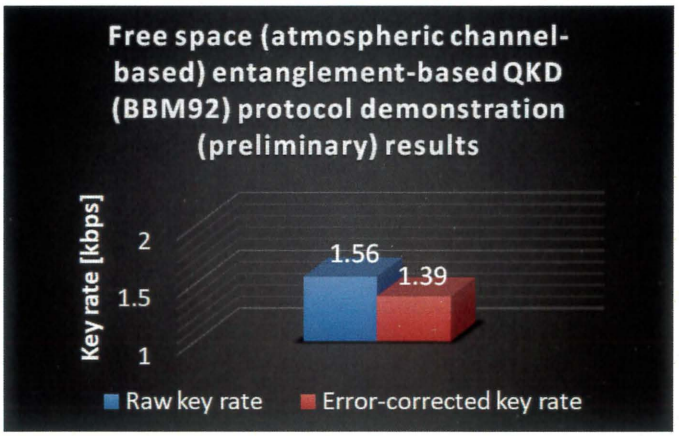
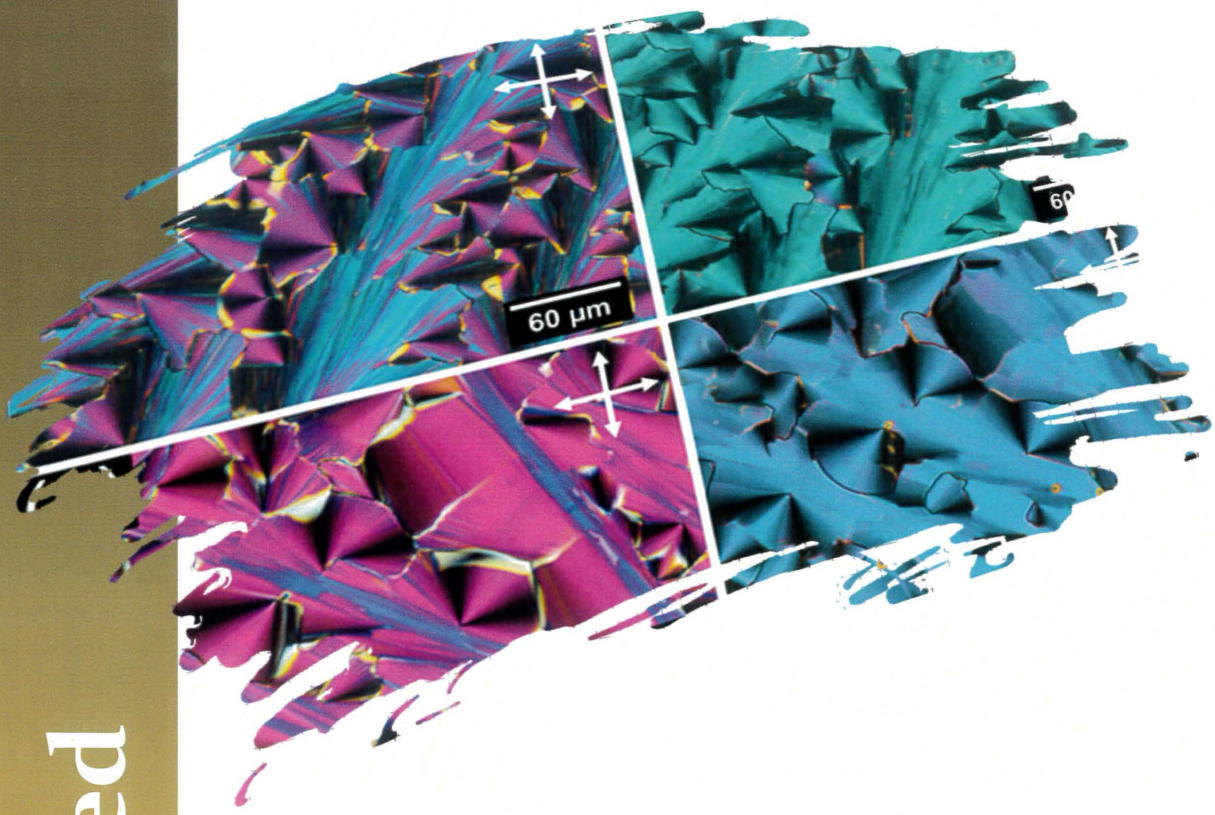


Figure 22. Preliminary results for entanglement based QKD (BBM 92 protocol) demonstration through a free space atmospheric channel between two buildings at RRI.

Another project in the domain of secure quantum communications wherein concerted progress was made in 2020 was under the **India Trento Programme on Advanced Research** or the **ITPAR programme** of the Department of Science and Technology. Under this project, RRI is leading a multi institutional collaboration with University of Trento in Italy. Urbasi Sinha at RRI is the principal investigator of the project with Dipankar Home at Bose Institute Kolkata, Prasanta Panigrahi at IISER Kolkata and Guruprasad Kar at ISI Kolkata as Co-PIs.

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, polymer melts or solutions, paint and many biological materials like cells and tissue. 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 2020-21

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. 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 2020-21 was on design and synthesis of novel LC's and studying their physical properties, phase transitions and electro-optic properties.

Phase Transition and Electro-Optics of Liquid Crystals

Crystal polymorphism of 8OCB liquid crystal consisting of strongly polar rod-like molecules

During the past year, Arun Roy and Subhadip Ghosh reported detailed experimental studies on the different crystal polymorphs of 8OCB (40-octyloxy-4-cyanobiphenyl) obtained by cooling the sample from its melt. Along with a stable crystal phase known as commercial powder (CP) phase it was shown that 8OCB exhibits various metastable crystal phases such as square-plate, needle phase and long parallelepiped (PP) phase. They identified the metastable crystal state often found on cooling the sample from its melt as PP phase which transforms to stable CP phase on aging at room temperature or by heating it above 312 K. Based on the experimental results, the stable CP crystal phase of 8OCB was found to exist not in single homogeneous phase but a coexistence of fibrillar nano- crystallites embedded in an amorphous phase. The heterogeneous nature of its stable crystal state is an intriguing feature of this pure compound consisting of relatively small rod-like molecules with a strong dipole moment along their long axis. This work has been published in *RSC adv., 11, 4958 (2021).*

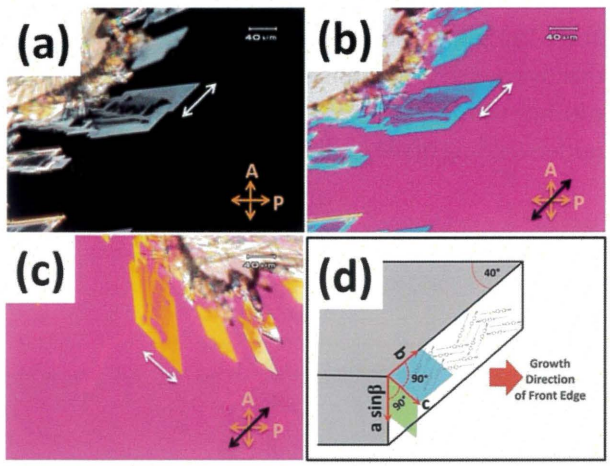


Figure 1. The POM textures of a strip of PP phase between crossed polarisers: (a) without λ-plate, (b) with the slow axis of the λ-plate parallel to the front edge and (c) with the slow axis of the λ-plate perpendicular to the front edge. The white double headed arrow indicates the major axis of the effective refractive index ellipse within the strip. (d) The schematic representation of the molecular organisation within the strip.

[Subhadip Ghosh and Arun Roy]

Observation of banded spherulitic crystal growth in a liquid crystal consisting of rodlike molecules

The spherulitic growth of crystal is a ubiquitous phenomenon exhibited by many different types of materials. In spherulitic growth, the crystalline seed after nucleation grows with a spherical growth front in contrast to the growth dictated by the crystallographic symmetries. In general, a crystalline seed after nucleation grows having a discrete crystallographic orientation. But in certain physical conditions, some materials are incapable of such growth and instead grow as spherulite with continuous orientational symmetry. A variety of materials are known to form spherulite from its melt, solution, gel and solid phase. A large number of studies since its discovery have established the generality of this phenomenon though the detail theoretical understanding of the growth mechanism is still lacking.

In 2020-21, Arun Roy and PhD students Subhadip Ghosh and Dipak Patra studied the formation of banded spherulite by a pure liquid crystalline compound consisting of relatively small rod-like molecules and showed that the rhythmic growth of crystal-rich and crystal-poor zones is the underlying mechanism for the formation of these banded spherulites. The banded spherulites observed in this compound were formed by alternating concentric domains of crystal- rich and crystal-poor zones during the growth of the spherulites from the melt. The alternating crystal- rich and crystal-poor regions were found to change the effective birefringence periodically along the radial direction of the domain giving rise to the concentric interference colour bands between crossed polarizers. To the best of their knowledge, this is the first report of formation of banded spherulite due to rhythmic growth in a pure compound without any twist of its fibrillar crystallites. This work is under preparation for publication.

[Subhadip Ghosh, Dipak Patra and Arun Roy]

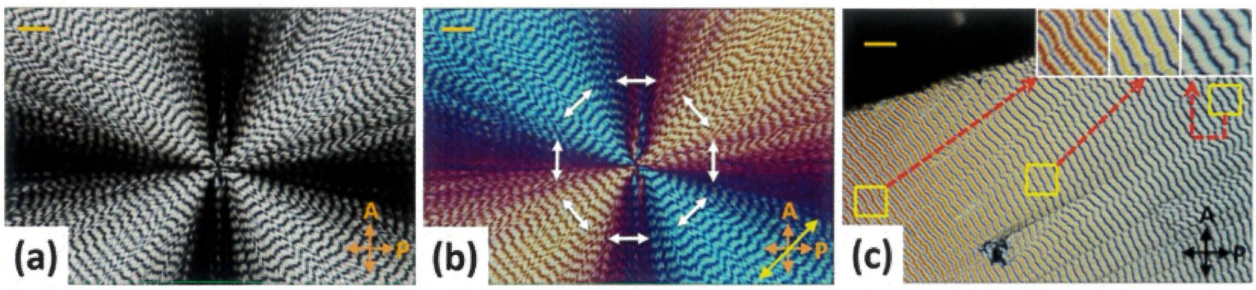


Figure 2: (a) The POM texture of a banded spherulite formed between two coverslips under crossed polarisers. (b) The POM texture after introducing a λ-plate in the optical path. The white double arrows around the seed indicate the orientations of major refractive index lying on the sample plane. (c) The banded spherulite texture between two coverslips for relatively thicker sample. The insets show colour variation in bands at three different regions of the domain with slightly different thicknesses. The scale bars represent 20 ìm distance.

Evidence of oblique columnar phase ordering in bent-core liquid crystal

The synthesis and experimental investigations on two homologues of liquid crystal materials comprised of anisotropic bent-core banana shaped molecules was reported by Arun Roy, Vishnu Deo Mishra and H T Srinivasa. In contrast to the B-phases usually observed for this type of molecules, both of the compounds studied exhibited an oblique columnar liquid crystal phase. In this columnar phase, molecules arranged themselves in 1D liquid-like columns which formed a 2D oblique rectangular lattice in the plane perpendicular to the column axes. The X-ray diffraction studies confirmed the oblique columnar ordering in this mesophase. The low value of dielectric constant as well as polarization switching current measurements indicated the absence of polarization in this columnar phase. It was observed that in spite of the absence of polarization, the mesophase can be switched irreversibly to a higher birefringent texture on application of a low frequency electric field across a planar aligned sample. This work is under preparation for publication.

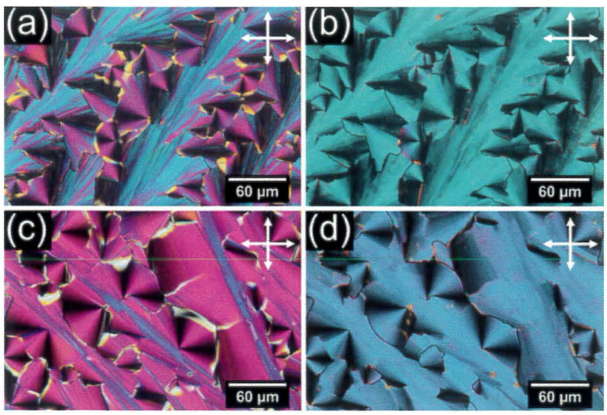


Figure 3. The POM textures of compound 6c(n10) in the columnar X1 phase at temperature 140 °C (a) at zero electric field (b) at E=26V/µm and of 6e(n12) in the Y1 phase at temperature 142 °C (c) at zero electric field (d) E =30 V/µm.

[Vishnu Deo Mishra, H T Srinivasa and Arun Roy]

Mechanical Properties of Soft Materials

Strain localization and yielding dynamics in disordered collagen networks

Collagen is the most abundant extracellular-matrix protein in mammals and the main structural and load-bearing element of connective tissues. Collagen networks show remarkable strain-stiffening which tune the mechanical functions of tissues and regulate cell behaviours. Linear and non-linear mechanics of in-vitro disordered collagen networks have been widely studied using rheology for a range of self-assembly conditions in recent years. However, the correlation between the onset of macroscopic network failure and local deformations is not well understood in these systems.

Using shear rheology and in-situ high-resolution boundary imaging, Swarnadeep Bakshi, Vaisakh V M, Ritwick Sarkar and Sayantan Majumdar studied the yielding dynamics of in-vitro reconstituted networks of uncrosslinked type-I collagen and found that in the non-linear regime, the differential shear modulus (K) of the network initially increases with applied strain and then begins to drop as the network starts to yield beyond a critical strain (yield strain). Measurement of the local velocity profile using colloidal tracer particles revealed that beyond the peak of K, strong strain-localization and slippage between the network and the rheometer plate sets in that eventually leads to a detachment. This observation was generalized for a range of collagen concentrations, applied strain ramp rates, as well as, different network architectures obtained by varying the polymerization temperature. Furthermore, using a continuum affine network model, a state diagram showing the dependence of yield-stain and -stress on the reduced persistence length and mesh size was mapped out. These findings can have broad implications in tissue engineering and in designing

highly resilient biological scaffolds. This work is published in: *Soft Matter, 2021, 17, 6435.*

[Swarnadeep Bakshi, Vaisakh V M, Ritwick Sarkar and Sayantan Majumdar]

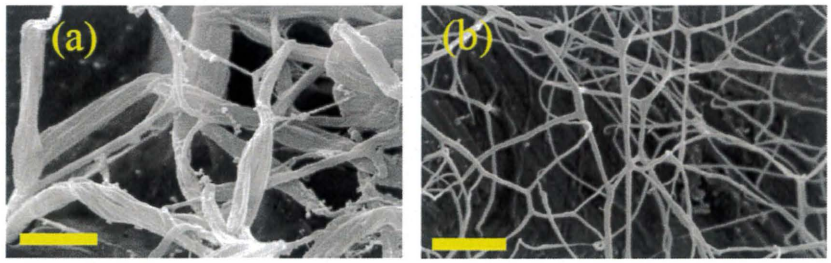


Figure 4. Freeze-fracture SEM image of collagen polymerized at (a) 4 °C (Scale = 1 mm) and (b) 25 °C (Scale = 2 mm). More bundled networks are obtained at lower temperature.

Effect of adhesive interaction on non-linearity and dissipation in a granular gel of amorphous particles

Stress induced yielding/fluidization in disordered solids, characterized by irreversibility and enhanced dissipation, is important for a wide range of industrial and geological processes. Although, such phenomenon in thermal systems has been extensively studied, they remain poorly understood for granular solids.

In a recent work, Sebanti Chattopadhyay, Sharadhi N Raj and Sayantan Majumdar used oscillatory shear rheology and in-situ optical imaging to study energy dissipation in a dense granular suspension of cohesive particles that form yield stress solids well below the isotropic jamming point obtained in the limit of hard sphere interaction. For small applied strain values, they observe randomly distributed plastic rearrangements correlating with the spatiotemporal fluctuations in local velocity. In this strain range, they also observed significant strain stiffening. At larger strain values beyond fluidization, plastic rearrangements significantly increased and became mostly concentrated near the shearing boundaries. Strain stiffening and random velocity fluctuations were also found to disappear in this regime. They showed that such complex interplay between non-linearity and dissipation can be effectively captured by a single parameter termed as normalized energy dissipation (E_N). Furthermore, by directly measuring the critical jamming packing fractions under different conditions using particle settling experiments, they propose a detailed phase diagram that unravels the role of inter-particle interactions in controlling E_N for a wide range of packing fractions and strain amplitudes. This work is currently under review.

[Sebanti Chattopadhyay, Sharadhi N Raj, Sayantan Majumdar]

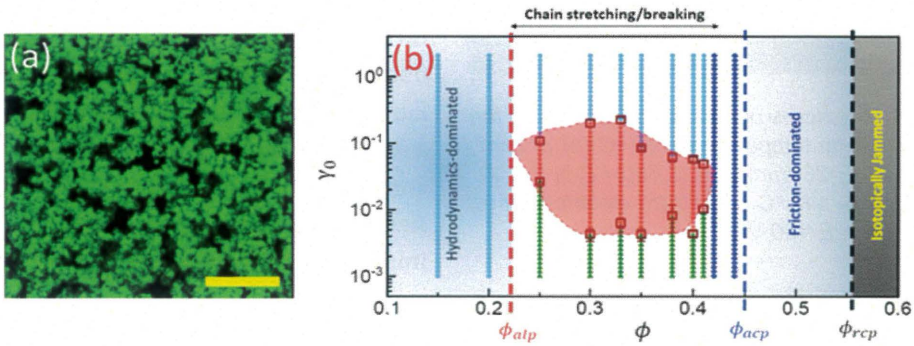


Figure 5. (a) Typical confocal image of a settled bed formed by dispersing CS particles in paraffin oil. The particles form fractal clusters. The scale bar is 150 mm. (b) Detailed phase diagram in the parameter plane of applied strain amplitude and particle volume fraction. Red coloured region indicates the strain stiffening response.

Structural signature of dynamic shear jamming in suspensions of fractal nanotube clusters

Under applied stress, viscosity of many dense particulate suspensions can increase drastically, a response known as discontinuous shear-thickening (DST). In some cases, the applied stress can even transform the suspension to a solid-like shear jammed state (SJ). Although SJ has been probed for suspensions with particles having well-defined geometries, such a phenomenon for fractal objects has not been explored.

During the year in report, Sarika C K, Sayantan Majumdar along with collaborator A K Sood studied stress induced flow behaviour in a suspension of fractal flocs of multi-walled carbon nanotubes (MWCNT) in NMP under confinement. Using rheology and in-situ optical imaging, they observed a direct transition from a flowing to a SJ state at an onset volume fraction significantly lower than that for conventional dense suspensions. Such remarkable property of the system enabled them to probe the anisotropic stress response and fragility correlating with the contact dynamics of the SJ state under stress reversal. They showed that the transition from a flowing to a SJ state is related to the structural rearrangements in the system as captured by the probability distribution function of transmitted optical intensity through the sample and the computable information density (CID). Furthermore, using a generalized Wyart-Cates model, they propose a phase diagram that captures the observed SJ behaviour over a wide range of concentration and applied stress values.

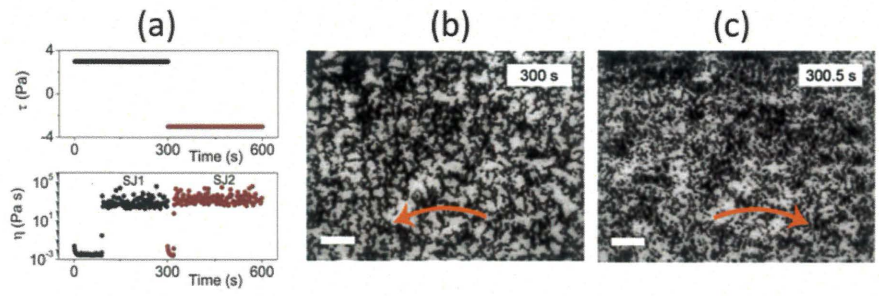


Figure 6. (a) Melting of shear-jammed state under stress reversal in a system of fractal MWCNT flocs dispersed in NMP. The viscosity changes by several orders of magnitude. Optical images showing the floc structure before (panel (b)) and after (panel (c)) such melting. For (b) and (c) scale bar = 1 mm.

[Sarika C K, Sayantan Majumdar and A K Sood (Indian Institute of Science, Bangalore)]

Role of actin filament alignment on mechanical hysteresis in cross-linked networks

Cells dynamically control their material properties through remodelling of the actin cytoskeleton, an assembly of cross-linked networks and bundles formed from the biopolymer actin. Earlier it was found that cross-linked networks of actin filaments reconstituted in vitro can exhibit adaptive behaviour [Majumdar et al.; *Soft Matter, 2018*] and thus serve as a model system to understand the underlying mechanisms of mechanical adaptation of the cytoskeleton. In these networks, training, in the form of applied shear stress, can induce asymmetry in the nonlinear elasticity.

Recent efforts by Sayantan Majumdar and collaborators Danielle R Scheff, Steven A Redford, Chatipat Lorpaiboon, Aaron R Dinner and Margaret L Gardel has been towards exploring control over this mechanical hysteresis by tuning the concentration and mechanical properties of cross-linking proteins in both experimental and simulated networks. It was found that this effect depends on two conditions: the initial network must exhibit nonlinear strain stiffening, and filaments in the network must be able to reorient during training. Hysteresis depends strongly and non-monotonically on cross-linker concentration, with a peak at moderate concentrations. In contrast, at low concentrations, where the network does not strain stiffen, or at high concentrations, where filaments are less able to rearrange, there is little response to training. Additional investigations on the

effect of changing cross-linker properties showed that longer or more flexible cross-linkers enhance hysteresis. Remarkably plotting hysteresis against alignment after training yielded a single curve regardless of the physical properties or concentration of the cross-linkers. This work is published in: *Soft Matter, 2021, 17, 5499*.

[Sayantan Majumdar and collaborators from University of Chicago, Illinois: Danielle R Scheff, Steven A Redford, Chatipat Lorpaiboon, Aaron R Dinner and Margaret L Gardel]

Structure, Dynamics and Rheology of Colloids

Quantifying the destructuring of a thixotropic colloidal suspension using falling ball viscometry

The settling dynamics of falling spheres inside a Laponite suspension was studied by Rajkumar Biswas, Debasish Saha and Ranjini Bandyopadhyay. Laponite is a colloidal synthetic clay that shows physical aging in aqueous suspensions due to the spontaneous evolution of inter-particle electrostatic interactions. In their experiments, millimeter-sized steel balls were dropped in aqueous Laponite suspensions of different ages (i.e., time elapsed since sample preparation). The motion of the falling balls was captured using a high-speed camera, and the velocities of their centroids were estimated from the images. Interestingly, it was observed that balls of larger diameters fail to achieve terminal velocity over the entire duration of the experiment. They proposed a mathematical model that accounts for rapid structural changes (expected to be induced by the falling ball) in Laponite suspensions whose aging time scales are much slower than the time of fall of the ball. For a range of ball sizes and Laponite suspension ages, their model correctly predicts the time dependence of the ball velocity. Furthermore, fits to the model allowed them to estimate the rates of destructuring of the thixotropic suspensions due to the passage of the falling ball. This work is now published. *https://doi.org/10.1063/5.0035093*

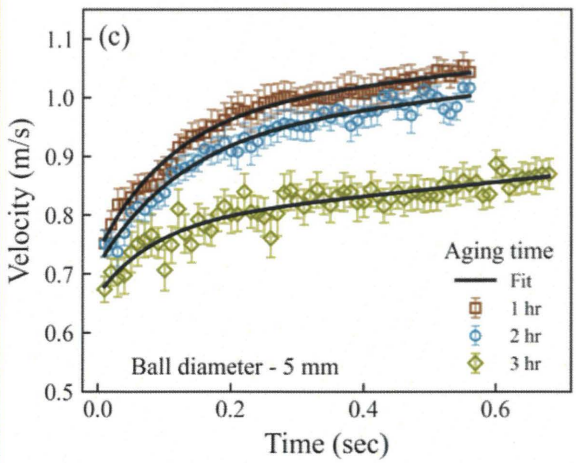


Figure 7. Velocities of the ball centroids for balls of diameter 5mm that are dropped in Laponite suspensions of different aging times (t_W). Colored symbols represent experimental data, colored vertical bars are the corresponding error bars and continuous black lines are fits to the theoretical model.

[Rajkumar Biswas, Debasish Saha and Ranjini Bandyopadhyay]

Competing effects of solvent microstructures and electrostatic interactions on the aging dynamics and rheology of aqueous suspensions of a soft colloidal clay

Efforts during the past year by Chandeshwar Mishra, V Thrithamara Ranganathan and Ranjini Bandyopadhyay were towards studying the competing effects of solvent microstructure and inter-particle electrostatic interactions on the microscopic dynamics and rheology of aging colloidal smectite (Laponite) clay suspensions. Using dynamic light scattering and rheometry, they reported changes in suspension dynamics when different additive molecules, both dissociating and non- dissociating, are incorporated in the medium. They found that the addition of glucose enhances hydrogen bonding in water, increases osmotic pressure gradients and results in accelerated suspension aging. In contrast, the presence of N,N-Dimethylformamide in water disrupts hydrogen bonding, reduces osmotic pressure gradients and suppresses suspension aging. Salts such as sodium chloride and potassium chloride dissociate

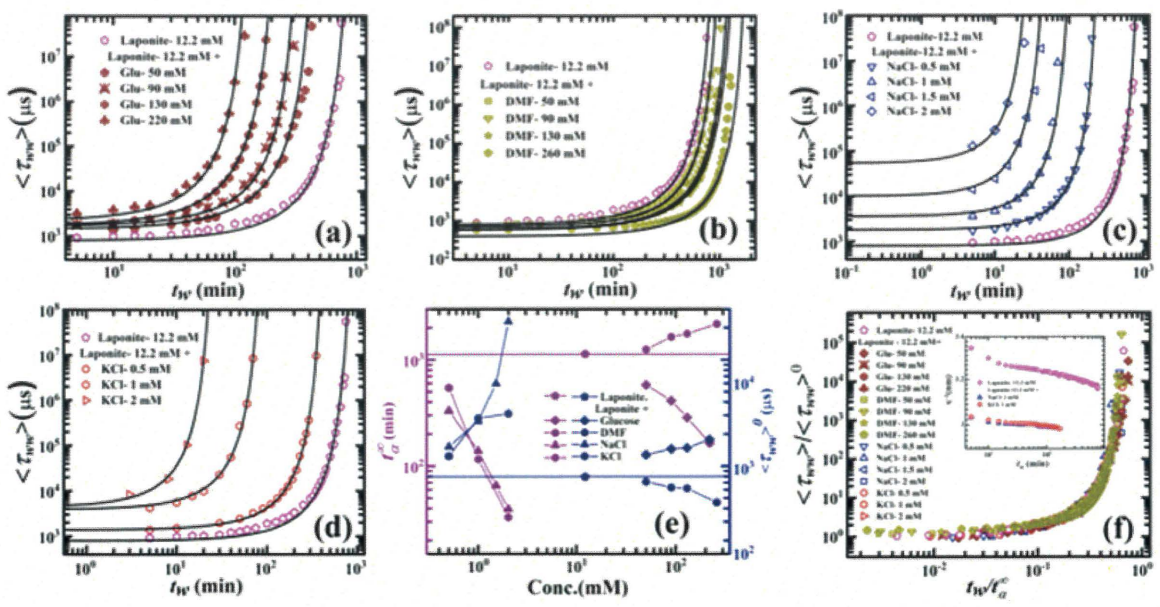


Figure 8. Mean slow relaxation time $<\tau_{ww}>$ vs. waiting time t_w for 12.2 mM aqueous Laponite suspensions without and with different concentrations of additives (a) glucose (Glu), (b) DMF, (c) NaCl and (d) KCl. The solid lines are fits to theory. (e) Horizontal and vertical shift factors, $\mathbf{t}\,\alpha^{\infty}$ (Vogel time) and $<\tau_{ww}>0$, of aqueous Laponite suspensions for different concentrations of additives. (f) Superposition of normalized mean slow relaxation times $<\tau_{ww}>/<\tau_{ww}>0$ vs. normalized waiting time $\mathbf{tw}\,/\,\mathbf{t}\,\alpha^{\infty}$ for aqueous Laponite suspensions without and with different concentrations of additives. Inset of (f) shows Debye screening lengths ($\hat{e}^{-1}$) of pure 12.2 mM aqueous Laponite suspension and 12.2 mM Laponite suspensions in the presence of 1 mM NaCl and KCl as a function of waiting time t_w.

into ions when added to water, while also locally altering water microstructure. Laponite suspensions in the presence of dissociating salts showed accelerated kinetic arrest, which they attribute to the dominance of electrostatic interactions over changes in solvent microstructure. Pre-heated and post-heated Laponite suspensions were prepared, wherein temperature is raised to different predetermined values before and after the addition of Laponite colloids respectively. Faster kinetic arrest with increasing temperatures was observed, with the aging being more rapid in pre-heated clay suspensions when compared to post-heated ones at the same temperature. While these experiments using non-dissociating molecules reveal the dominance of solvent microstructure on suspension dynamics and rheology, solvent microstructural effects were considerably suppressed in the presence of dissociating molecules and for the different suspension temperature histories studied. The microscopic dynamics of aging Laponite suspensions showed self-similar time-evolution, while their nonlinear rheological responses were sensitive to solvent temperature and the presence of additive molecules. Finally, the aging dynamics and rheology of the suspensions were corelated with sample microstructural details, visualized using cryogenic electron microscopy. This study revealed that solvent microstructure is a key parameter in determining the dynamics and rheology of suspensions of smectite clay colloids. *https://arxiv.org/abs/2009.12741*

[Chandeshwar Mishra, V Thrithamara Ranganathan and Ranjini Bandyopadhyay]

Emergent patterns and stable interfaces during radial displacement of a viscoelastic fluid

The displacement of a more viscous fluid by a less viscous fluid renders the fluid- fluid interface unstable and leads to intricate patterns called viscous fingers. Since the fluids experience shear during displacement, it should be possible to influence the emergence of patterns and instability dynamics through rheological parameters, such as elasticity or relaxation time in case of a viscoelastic fluid. In a recent article, Palak, Ranjini Bandyopadhyay along with collaborators Rahul Satyanath and Sreeram Kalpathy recorded and analyzed the interfacial fingering patterns that emerge when a Newtonian fluid (glycerol-water mixtures of different viscosities) displaces a shear-thinning viscoelastic fluid (aqueous cornstarch suspensions of varying concentrations) in a radial Hele-Shaw cell. The found that as the ratio of viscosities of the inner and outer fluids increased, radial branched patterns are replaced by more stable interfaces that display finger coalescence. Increases in the viscosity of the displacing fluid and the concentration-dependent elasticity of the outer viscoelastic fluid both led to significant suppression of interfacial instabilities. A linear stability analysis of the interface, using viscosity ratio as the only control parameter, was employed to predict a dominant wavelength of interfacial perturbation. They showed that the perturbation wavelength computed numerically matches closely with the spacing between fingers measured experimentally at the onset of interfacial instability. This work is available at *https://arxiv.org/abs/2010.10423*.

[Palak, Ranjini Bandyopadhyay and collaborators from IIT Madras: Rahul Satyanath and Sreeram Kalpathy]

DC field coupled evaporation of a sessile gold nanofluid droplet

In 2020-21 A W Zaibudeen and Ranjini Bandyopadhyay reported coffee stains due to the drying of aqueous suspensions of CTAB capped gold nanorods (Au-NRs) in the presence of a DC electric field. The coffee stain was characterized by the formation of distinct microscale structures in different regions. A typical coffee ring edge with distinct domains was observed due to outward capillary flow, with the Au- NRs assembled in a smectic phase (parallel to the substrate) in a zero DC field. Application of a DC electric field resulted in the flipping of the Au-NRs clusters at the coffee ring edge in the direction of the field. These results were understood in terms of dipolar interactions. At the inner boundary of the coffee ring edge, clusters of Au-NRs were observed without any ordering or with short range order, formed due to Marangoni eddies. Moving inwards towards the centre of the evaporated droplet, they noted the formation of a dark depletion region that is devoid of particles, which is followed by the random deposition of Au-NRs. The depletion region is believed to form due to the deposition of CTAB molecules during the final stage of droplet drying. Interestingly, arrays of Au-NRs are also found to deposit outside the coffee ring. This observation is a consequence of the opposite charges on the Au-NRs and substrate, which results in an autophobing-induced depinning effect or droplet retraction.

[A W Zaibudeen and Ranjini Bandyopadhyay]

Effective chitosan-silica-TiO_2 hybrid nanocomposite gels for adsorption of dye: Synthesis, characterization and adsorption kinetics

A nanocomposite gel that efficiently adsorbs organic dye (methylene blue) dye from water was synthesized during the past year by Tamal Sarkar, Chandeshwar Mishra and Ranjini Bandyopadhyay. This hybrid gel was synthesized using chitosan, silica and titanium dioxide (TiO_2) nanoparticles as precursors. The nanocomposite gel was characterized by scanning electron cryomicroscopy (cryo SEM), X-ray diffraction (XRD), and rheometry. In particular, the linear viscoelastic properties of the nanocomposite gel were analyzed by a rheometer. The nanocomposite gel was further utilized to adsorb methylene blue (MB) dye (1-20 ppm) from water. Effects of contact time, pH of the solvent, amount of adsorbent, initial dye concentration on the removal

percentage, were probed systematically. It was established that the hybrid gel is an excellent adsorbent due to the porous nature of silica, the binding capability of chitosan and the photocatalytic activity of TiO_2 NPs. This nanocomposite gel can therefore be used for treating wastewater containing dyes.

[Tamal Sarkar, Chandeshwar Mishra and Ranjini Bandyopadhyay]

Physics of Lipid Membranes and Polyelectrolytes

Effect of pH on the phase behavior of DMPC bilayers

Anindya Chowdhury, Sreeja Sasidharan and V A Raghunathan studied the effect of acidic pH on the phase behaviour of the zwitterionic lipid 1,2-dimyristoyl-sn-glycero-3-phosphocholine (DMPC) using differential scanning calorimetry and x-ray scattering. Dispersions of DMPC in HCl solutions of pH = 4 and 3 were found to behave identical to dispersions in water. The main transition temperature increased sharply and the pre-transition disappeared at lower pH. An untilted gel phase was observed at pH = 2 and 1, in contrast to the tilted gel phase found at higher pH. The relatively large periodicity of the untilted gel phase, in comparison to that of the tilted gel phase occurring near neutral pH, clearly demonstrated the simultaneous charging and dehydration of the headgroups as the pH approaches the pK of the phosphate group. Headgroup dehydration at low pH also led to the formation of DMPC crystallites and the inverted hexagonal phase at low and high temperatures, respectively, after a few days of incubation. These results show the significant effect of acidic pH on the phase behaviour of zwitterionic lipids.

[Anindya Chowdhury, Sreeja Sasidharan and V A Raghunathan]

Biophysics

Biophysics of Axons

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

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

with the internal cytoskeleton—an axisymmetric arrangement of different biopolymers and their associated proteins. This cytoskeleton highly dynamic as the polymers undergo turnover via constant polymerisation-depolymerisation processes and are acted upon by molecular motors which can generate active stresses on the filaments. Thus, the axon is a structure which is maintained under a dynamic steady state where the different membrane and cytoskeletal forces are balanced against each other. Any changes in this dynamic balance can lead to abnormalities in the axonal form and function. This is particularly significant for neuronal cells as they do not divide unlike other cells in a human body and are rarely replenished when lost. This makes the nervous system particularly susceptible to degeneration causing debilitating conditions. Axons, owing to their extreme lengths, are particularly vulnerable.

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

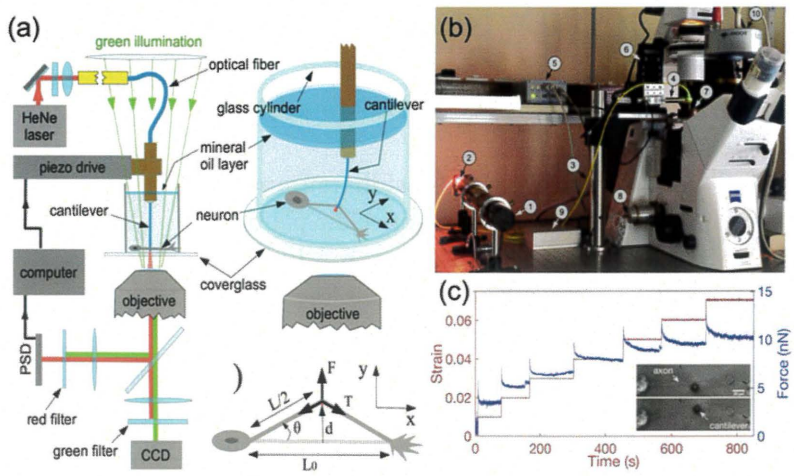


Figure 9. (a) A schematic of the Micro-Extensional Rheometer designed and developed at RRI and the scheme used to stretch live axons to probe their viscoelastic responses. (b) A photograph of the setup. (c) Example force response of an axon when subjected to a step-strain stretching protocol (see publication: https://doi.org/10.7554/eLife.51772).

The research work carried out at the Cell BioPhysics lab during the year in report is given below.

Non-linear mechanical responses of axons

Sukh Veer (PhD student) has followed up on the experiments performed earlier by Sushil Dubey using the Micro- Extensional Rheometer developed at RRI. He has investigated the response of axons to cyclic strains of varying magnitude and this reveals interesting data which will help to further test and improve the theoretical model developed earlier. Sukh Veer also performed some novel experiments where he looked at buckling of axons when released from a stretched state. Such experiments have proven to be very useful in understanding the viscoelastic response of microtubules which was hard to explore with earlier experiments. He has also developed a PRMS based stretch device which is being tested. This work is being done with collaborators Aurnab Ghose and Andrew Callan- Jones.

[Sukh Veer, Pramod Pullarkat and collaborators Aurnab Ghose, IISER-Pune and Andrew Callan-Jones, Univ. of Paris, France]

Myosin-II independent contractility of actin bundles in membrane nano-tubes

Mohammad Arsalan (PhD student) has been conducting experiments on membrane nano-tubes pulled out of axons using optical tweezers. He has observed that actin filaments invade these tubes and generate active contractile forces on the bead used to extract the tether. Various experiments conducted by Arsalan and a project student Susav Pradhan has revealed that this process is independent of myosin-II

molecular motors which are the main contractile force generator on actin cytoskeleton. By conducting a series of experiments on genetically modified cells with the help of Serene Rose David they were able to show that this force generation may be due to a new mechanism involving allosteric interaction of actin filaments with an actin binding protein called ADF. Arsalan has also developed a simple model for force generation which is able to reproduce the rich variety of features seen in the experimental force time series.

[Mohammad Arsalan, Susav Pradhan, Serene Rose David and Pramod Pullarkat]

Laser ablation of axons to study axonal mechanics

Ashish Mishra (PhD student) has performed experiments on ablating or cutting axons using a pico-second laser in order to investigate their retraction behaviour. Such studies are expected to provide information on how the various cytoskeletal components respond to ablation. Apart from providing mechanistic insights into force balance between these components, these studies will also help us understand axon degeneration process after injury. Ashish is now analysing the data he has collected using several cytoskeletal modifications. This project is in collaboration with the group of Aurnab Ghose.

[Ashish Mishra, Aurnab Ghose (IISER-Pune) and Pramod Pullarkat]

A microfluidic method to study axonal membrane dynamic

Deepak Mehta (PhD student) has developed a fully automated microfluidic flow device to investigate axonal membrane dynamics. This device consist of programable valve manifold and temperature control apart from a computer controlled syringe pump system. He has performed various tests and calibration of the device and it is now ready for performing experiments. This device will be used to study axonal membrane tension regulation and also use fluid drag force as a means of cyclically loading axons while simultaneously applying various biochemical cytoskeleton modifiers to the axons to study their effects on mechanical response.

[Deepak Mehta and Pramod Pullarkat]

Nanoscale biophysics of Biological systems

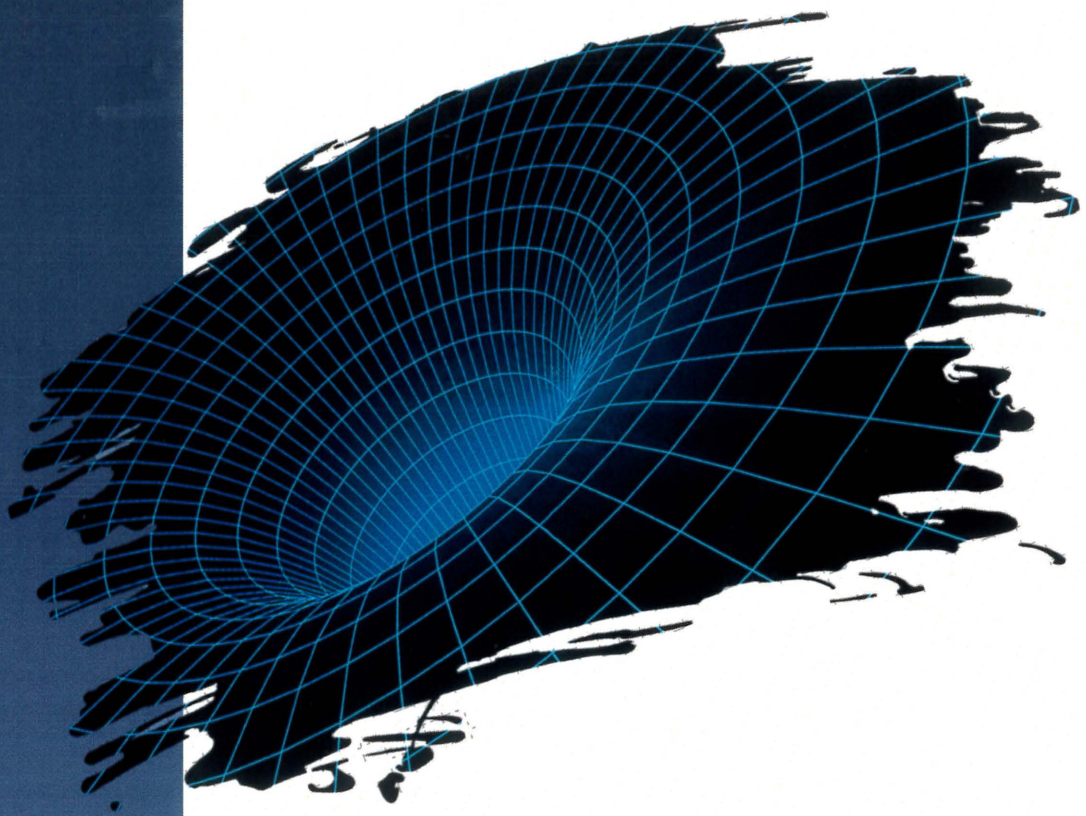
The research interests of Gautam Soni's Nanoscale biophysics of biological systems laboratory at RRI are primarily guided by the role of force in biophysical structure formation and its synergy with functional dynamics. Research efforts are towards understanding mechanisms of force-sensing as well as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

Research efforts by Gautam Soni, his students and collaborators resulted in two publications during the past year:

(1) Fingerprinting branches on supercoiled plasmid DNA using quartz nanocapillaries. Sumanth Kumar Maheshwaram, Koushik Sreenivasa and Gautam Vivek Soni *Nanoscale (2021), 13, 320-331*

(2) Measurement of Alcohol-Dependent Physiological Changes in Red Blood Cells Using Resistive Pulse Sensing. Saurabh Kaushik, Manohara Mahadeva, Kandhasamy Durai Murugan, Varadharajan Sundaramurthy, and Gautam Vivek Soni *ACS Sensors (2020), 5(12): 3892–3901*

theoretical physics



Overview

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

Focus 2020-21

Statistical Physics

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

Active particle dynamics

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

Active Brownian motion with directional reversals

Active Brownian motion with intermittent direction reversals are common in a class of bacteria like Myxococcus Xanthus and Pseudomonas putida. Recent research by RRI theorists Ion Santra, Urna Basu and Sanjib Sabhapandit has shown that, for such a motion in two dimensions, the presence of the two time scales set by the rotational diffusion constant D_R and the reversal rate γ give rise to four distinct dynamical regimes showing distinct behaviors. They analytically computed the position distribution which showed a crossover from a strongly non-diffusive and anisotropic behavior at short-times to a diffusive isotropic behavior via an intermediate regime. It was found that the marginal distribution in the intermediate regime shows an exponential or Gaussian behavior depending on whether γ is larger or smaller than D_R. They found the persistence exponents in the four regimes. In particular, it was shown that a novel persistence exponent $\alpha = 1$ emerges due to the direction reversal. This work is now published: *Phys. Rev. E 102, 052129 (2020)*

[Ion Santra, Urna Basu and Sanjib Sabhapandit]

Active Brownian motion in two-dimensions under stochastic resetting

Stochastic resetting, which refers to intermittent interruption and restart of a dynamical process, has been a subject of immense interest in recent years. Efforts at the Institute are towards studying the effect of resetting on interacting particle systems and active dynamics. Urna Basu along with visiting students Vijay Kumar and Onkar Sadekar have studied the position distribution of an active Brownian particle (ABP) in the presence of stochastic resetting in two spatial dimensions. They considered three different resetting protocols : (I) where both position and orientation of the particle are reset, (II) where only the position is reset, and (III) where only the orientation is reset with a certain rate r. They have shown that in the first two cases the ABP reaches a stationary state. Using a renewal approach, they calculated exactly the stationary marginal position distributions in the limiting cases when the resetting rate r is much larger or much smaller than the rotational diffusion constant D_R of the ABP and have found that, in some cases, for a large resetting rate, the position distribution diverges near the resetting point; the nature of the divergence depending on the specific protocol. For the orientation resetting, there is no stationary state, but the motion changes from a ballistic one at short-times to a diffusive one at late times. The short-time non-Gaussian marginal

position distributions was also characterized using a perturbative approach. This work is now published: *Phys. Rev. E 102, 052129 (2020).*

[Urna Basu and VSP students Vijay Kumar (IISER Kolkata) and Onkar Sadekar (IISER Pune)]

Run-and-tumble particle in inhomogeneous media in one dimension

Sanjib Sabhapandit and collaborators Prashant Singh and Anupam Kundu investigated the run and tumble particle (RTP), also known as persistent Brownian motion, in one dimension. A telegraphic noise $\sigma(t)$ drives the particle which changes between ± 1 values with some rates. Denoting the rate of flip from 1 to -1 as R_1 and the converse rate as R_2, they considered the position and direction dependent rates of the form $R_1(x)=\left(\frac{|x|}{l}\right)^{\alpha}[\gamma_1\theta(x)+\gamma_2\theta(\gamma x)]$ and $R_2(x)=\left(\frac{|x|}{l}\right)^{\alpha}[\gamma_2\theta(x)+\gamma_1\theta(-x)]$ with $\alpha \geq 0$. For $\gamma_1 > \gamma_2$, they found that the particle exhibits a steady-state probability distribution even in an infinite line whose exact form depends on γ. For $\alpha = 0$ and 1, they solved the master equations exactly for arbitrary γ_1 and γ_2 at large t. From their explicit expression for time-dependent probability distribution $P(x,t)$ they found that it exponentially relaxes to the steady-state distribution for $\gamma_1 > \gamma_2$. On the other hand, for $\gamma_1 < \gamma_2$, the large t behaviour of $P(x,t)$ is drastically different than $\gamma_1 = \gamma_2$ case where the distribution decays as $t^{-1/2}$. Contrary to the latter, detailed balance was not obeyed by the particle even at large t in the former case. For general α, it was argued that the approach to the steady state in $\gamma_1 > \gamma_2$ case is exponential which they numerically demonstrate. On the other hand for $\gamma_1 \leq \gamma_2$, the distribution $P(x,t)$ does not reach a steady state, however possesses certain scaling behaviour. For $\gamma_1 = \gamma_2$ they derived this scaling behaviour as well as the scaling function rigorously whereas for $\gamma_1 < \gamma_2$ they provide heuristic arguments for the scaling behaviour and the corresponding scaling functions. They also studied the dynamics in semi-infinite line with an absorbing barrier at the origin and analytically computed the survival probabilities and first-passage time distributions for $\alpha = 0$ and 1. For general $\alpha \geq 0$, once again they computed the value of survival probability at large t and approach to it. Finally, they considered RTP in an finite interval $[0,M]$ and computed the associated exit probability from that interval for all α. All their analytic results matched with the numerical simulation of the same. This work has been published in *J. Stat. Mech. 2020, 083207 (2020).*

[Sanjib Sabhapandit and collaborators from ICTS, TIFR, Bengaluru: Prashant Singh and Anupam Kundu]

Run-and-tumble particles in two dimensions under stochastic resetting conditions

Ion Santra, Urna Basu and Sanjib Sabhapandit have studied the effect of stochastic resetting on a run-and-tumble particle (RTP) in two spatial dimensions. Considering a resetting protocol which affects both the position and orientation of the RTP: the particle undergoes constant-rate positional resetting to a fixed point in space and a random orientation, they computed the radial and x-marginal stationary- state distributions and showed that while the former approaches a constant value as $r \to 0$, the latter diverges logarithmically as $x \to 0$. On the other hand, both the marginal distributions decayed exponentially with the same exponent when they are far from the origin. The temporal relaxation of the RTP was studied and it was shown that the positional distribution undergoes a dynamic transition to a stationary state. Studies of the first-passage properties of the RTP in the presence of

resetting showed that the optimization of the resetting rate can minimize the mean first-passage time. A brief discussion of the stationary states for resetting a particle to an initial position with a fixed orientation was also provided. This work has been published in *Stat. Mech. 2020, 113206 (2020)*.

[Ion Santra, Urna Basu and Sanjib Sabhapandit]

Freezing transition in the barrier crossing rate of a diffusing particle

Sanjib Sabhapandit along with collaborator Satya Majumdar studied the decay rate $\theta(a)$ that characterizes the late time exponential decay of the first-passage probability density $F_a(t|0) \sim e^{-\theta(a)t}$ of a diffusing particle in a one dimensional confining potential $U(x)$, starting from the origin, to a position located at $a > 0$. For general confining potential $U(x)$ they have shown that $\theta(a)$, a measure of the barrier (located at a) crossing rate, has three distinct behaviors as a function of a, depending on the tail of $U(x)$ as $x \to -\infty$. In particular, for potentials behaving as $U(x) \sim |x|$ when $x \to \infty$, a novel freezing transition occurred at a critical value $a = a_c$, i.e, $\theta(a)$ increases monotonically as a decreases till a_c, and for $a \leq a_c$ it freezes to $\theta(a) = \theta(a_c)$. The results were established using a general mapping to a quantum problem and by exact solution in three representative cases, supported by numerical simulations. It was also shown that the freezing transition occurs when in the associated quantum problem, the gap between the ground state (bound) and the continuum of scattering states vanishes. This work has been published in *Phys. Rev. Lett. 125, 200601 (2020)*.

[Sanjib Sabhapandit and Satya Majumdar (LPTMS, CNRS, France)]

Optimal Control in Pandemics

The Covid-19 virus presents a global threat to life and livelihoods and throws up challenges which societies across the world have to learn to deal with. Pandemics are not new and there are mathematical models which have been developed over the years. The value of mathematical models is that they give us a simplified picture of the pandemic and let us explore the effects of different containment strategies, without performing costly and possibly fatal, social experiments. These models are the basis for a rational, science based social response to a serious threat. While models do have their limitations, they are steadily improving with time, experience and computational power. It is imperative for us to understand the predictions of these models and compare them with data and experience. In a recent publication Joseph Samuel and Supurna Sinha consider one of the simplest models of disease spread, the SIR model, which they analyse using a clock set by the virus. This use of the "virus time" permits a clean mathematical formulation of the problem. By optimizing the socio-economic cost for a fixed health cost enabled them to arrive at a strategy for navigating the pandemic. This involves adjusting the level of lockdowns in a controlled manner so as to minimise the socio-economic cost. This work is now published: *Phys. Rev. E 103, L010301 (2021)*.

[Joseph Samuel (RRI and ICTS, Bangalore) and Supurna Sinha]

Quantum Gravity

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

Loop Quantum Gravity

The construction of a fully quantum mechanical description of the gravitational interaction remains the outstanding open problem in fundamental theoretical physics. Quantum gravitational effects are expected to be dominant in extreme situations such as at the Big Bang and deep inside Black Holes. Einstein's General Relativity identifies gravitation with the geometry of space and time. Hence, a theory of Quantum Gravity is expected to revolutionise our very notions of spacetime and would herald a paradigm shift exceeding that following the discovery of Quantum Mechanics. One very successful approach to building such a theory goes by the name of Loop Quantum Gravity (LQG). It attempts to generalise the familiar techniques of quantum mechanics and quantum field theory and apply them to the context of gravitation. This generalization is technically and conceptually very intricate because, unlike the case of quantum field theory where the quantum fields evolve on a fixed spacetime, here it is the very geometry of spacetime which is dynamical. Hence one needs a generalization which does not rely on notions of a background fixed spacetime. While we have a fine understanding of how to describe quantum spatial geometry in LQG ('LQG kinematics') in the context of such a generalisation, a key open problem is how to satisfactorily describe quantum spacetime geometry ('LQGdynamics').

Gravitational dynamics — A novel shift in the Hamiltonian paradigm

LQG is an attempt at canonical quantization of a Hamiltonian formulation of General Relativity wherein one splits spacetime into space and time, reformulates the Einstein equations as Hamiltonian equations on phase space and seeks to replace Poisson brackets between functions by commutators between their operator correspondents. Clearly a deeper understanding of the classical dynamical equations of phase space is a prerequisite to the construction of a physically viable quantum dynamics. Recent research by Madhavan Varadarajan in collaboration with Abhay Ashtekar has revealed an intriguing and potentially deep geometrical interpretation of the classical Einstein equations written in Hamiltonian form. Specifically, Hamiltonian evolution in *time* can be understood in terms of certain generalizations of *spatial* geometrical transformations. This work not only has consequences for the construction of a quantum dynamics for LQG, it also connects with diverse areas such as recent double copy developments in perturbative gravity and conceptual puzzles pertaining to the relation of general relativity to its self-dual sector, and also leads to interesting mathematical physics issues connected with the infinite dimensional graded Lie algebras constructed herein.

It is well known that Einstein's equations assume a simple polynomial form in the Hamiltonian framework based on a Yang-Mills phase space. Madhavan Varadarajan and collaborator Abhay Ashtekar re-examined the gravitational dynamics in this framework and showed that time evolution of the gravitational field can be re-expressed as (a gauge covariant generalization of) the Lie derivative along a novel shift vector field in spatial directions. Thus, the canonical transformation generated by the Hamiltonian constraint acquires a geometrical interpretation on the

Yang-Mills phase space, similar to that generated by the diffeomorphism constraint. In classical general relativity this geometrical interpretation significantly simplifies calculations and also illuminates the relation between dynamics in the 'integrable' (anti)self-dual sector and in the full theory. For quantum gravity, it provides a point of departure to complete the Dirac quantization program for general relativity in a more satisfactory fashion. This gauge theory perspective may also be helpful in extending the 'double copy' ideas relating the Einstein and Yang-Mills dynamics to a non-perturbative regime. Finally, the notion of generalized, gauge covariant Lie derivative may also be of interest to the mathematical physics community as it hints at some potentially rich structures that have not been explored.

[Madhavan Varadarajan and Abhay Ashtekar (Penn State University, USA)]

Euclidean LQG dynamics: An electric shift in perspective

Recent work by Madhavan Varadarajan and Abhay Ashtekar recast classical gravitational evolution in *time* in terms of certain generalizations of *spatial* geometrical transformations known as diffeomorphisms. Key developments in foundational aspects of LQG kinematics during the 1990's have led to a fine understanding of the quantum implementation of spatial diffeomorphisms. Madhavan Varadarajan has used this LQG based implementation of quantum spatial diffeomorphisms in an intricate and delicate series of arguments so as to incorporate the geometrical features of classical gravitational evolution, uncovered in the recent work with Abhay Ashtekar, into a quantum dynamics for Euclidean Gravity. Progress in the physically relevant case of Lorentzian Gravity turns out to be contingent on a thorough understanding of the Euclidean case. Hence this work represents a significant breakthrough.

Loop Quantum Gravity (LQG) is a non-perturbative attempt at quantization of a classical phase space description of gravity in terms of SU(2) connections and electric fields. As emphasized recently, on this phase space, classical gravitational evolution in time can be understood in terms of certain gauge covariant generalizations of Lie derivatives with respect to a spatial SU(2) Lie algebra valued vector field called the Electric Shift. During the past year, Madhavan Varadarajan presented a derivation of a quantum dynamics for Euclidean LQG which is informed by this understanding. In addition to the physically motivated nature of the action of the Euclidean Hamiltonian constraint so derived, the derivation implies that the spin labels of regulating holonomies are determined by corresponding labels of the spin network state being acted upon thus eliminating the 'spin j-ambiguity' pointed out by Perez. By virtue of Thiemann's seminal work, the Euclidean quantum dynamics plays a crucial role in the construction of the Lorentzian quantum dynamics so that these considerations also have application to Lorentzian LQG.

[Madhavan Varadarajan]

Anomaly free quantum dynamics for Euclidean LQG

The conservative techniques of LQG are those of canonical quantization wherein one splits spacetime into space and time, reformulates the Einstein equations as Hamiltonian equations on phase space and seeks to replace Poisson brackets between functions by commutators between their operator correspondents. One key issue is then how to achieve this in a manner in which spacetime emerges from space and time in this Hamiltonian description. Since there is no preferred choice of background time, each choice of time corresponds to a distinct dynamical evolution and the emergence of classical spacetime is tied to the consistency of these (infinitely many) distinct dynamical evolutions. This consistency is captured by the particular structure of the Poisson Brackets between the Hamiltonians for these evolutions. Similarly, quantum spacetime is expected to emerge only if this algebraic structure is captured by the corresponding commutators. The commutator structure is very different and technically and conceptually much more intricate than that encountered in usual gauge theories.

Hence a demonstration that this commutator structure is implemented in quantum theory is both necessary and enormously challenging. In ongoing work, Madhavan Varadarajan has made significant progress on this issue in the context of the quantum dynamics which he recently constructed for LQG.

[Madhavan Varadarajan]

Propagation in quantum spin dynamics

Classical gravitational dynamics has the property that it propagates gravitational perturbations from one region of space to another. A folklore has developed in LQG based on influential work by Smolin in the 1990's that traditional LQG methods cannot yield a dynamics for quantum gravity which propagates quantum propagations, thus casting doubts on the efficacy of these methods. In collaborative work with Thiemann, Madhavan Varadarajan has shown that there is a key flaw in Smolin's reasoning and that this folklore has no validity. While the core of this work is complete, the ongoing pandemic has reduced collaborative efficiency and the finishing touches are slowly being put in place.

[Madhavan Varadarajan and Thomas Thiemann (Albert-Einstein-Institut, Germany)]

Causal Set Theory

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

A criterion for covariance in complex sequential growth models

The classical sequential growth model for causal sets provides a template for the dynamics in the deep quantum regime. This growth dynamics is intrinsically temporal and causal, with each new element being added to the existing causal set without disturbing its past. In the quantum version, the probability measure on the event algebra is replaced by a quantum measure, which is Hilbert space valued. Because of the temporality of the growth process, in this approach, covariant events (or observables) are measurable only if the quantum measure extends to the associated sigma algebra of events. This is not always guaranteed. During the past year, Sumati Surya and collaborator Stav Zalel have found a criterion for extension (and thence covariance) in complex sequential growth models for causal sets. They have found a large family of models in which the measure extends, so that all covariant events/observables are measurable.

[Sumati Surya and Stav Zalel, Imperial College, UK]

Entanglement entropy of causal set de Sitter horizons

de Sitter cosmological horizons are known to exhibit thermodynamic properties similar to black hole horizons. Sumati Surya, Nomaan X along with collaborator Yasaman Yazdi have studied causal set de Sitter horizons, using Sorkin's spacetime entanglement entropy (SSEE) formula, for a conformally coupled quantum scalar field. They have calculated the causal set SSEE for the Rindler-like wedge of a symmetric slab of de Sitter spacetime in d=2,4 spacetime dimensions using the Sorkin-Johnston vacuum state and found that the SSEE obeys an area law when the spectrum of the Pauli-Jordan operator is appropriately truncated in both the de Sitter slab as well as its restriction to the Rindler-like wedge. Without this truncation, the SSEE satisfies a volume law. This is in agreement with Sorkin and Yazdi's calculations for the causal set SSEE for nested causal diamonds in Minkowski spacetime, where they showed that an area law is obtained only after truncating the Pauli-Jordan spectrum. This work

explored different truncation schemes with the criterion that the SSEE so obtained obeys an area law.

[Sumati Surya, Nomaan X, and Yazaman Yazdi, Imperial College, UK and University of Alberta, Canada]

Entropy and the link action in the causal set path-sum

In causal set theory the gravitational path integral is replaced by a path-sum over a sample space n of n-element causal sets. The contribution from non-manifold-like orders dominates n for large n and therefore must be tamed by a suitable action in the low energy limit of the theory. Sumati Surya, Abhishek Mathur and Anup Anand Singh have extended the work of Loomis and Carlip on the contribution of sub-dominant bilayer orders to the causal set path-sum and showed that the link action suppresses the dominant Kleitman-Rothschild orders for the same range of parameters.

[Sumati Surya, Abhishek Mathur and Anup Anand Singh]

Nonequilibrium Quantum Dynamics

Equilibrium quantum dynamics has been investigated for almost a century now, and there are well-developed statistical mechanics descriptions both for closed (isolated/conservative) and open (coupled to bath/environment) quantum systems. There have also been tremendous efforts to generalize the above descriptions to out-of-equilibrium quantum systems. Yet, our current understanding of nonequilibrium quantum dynamics is still insufficient even after fifty years of intensive research. It is part of active research in recent years to know when and how a far-from-equilibrium closed quantum system relaxes to equilibrium. A system can be driven far-of-equilibrium by applying a mechanical (time-independent or -dependent electric or magnetic fields) perturbation or by keeping the system's boundaries in relative motion (shear) or maintained at different temperatures. When an out-of-equilibrium system does not relax to equilibrium, it generates two nonequilibrium systems: mechanical nonequilibrium systems and thermal nonequilibrium systems. Research along this direction at RRI broadly focuses on understanding nonequilibrium quantum dynamics in solid-state and atomic, molecular & optical (AMO) systems.

Random matrix spectral form factor in kicked interacting fermionic chains

The pattern in particles' motion can be regular for exactly-solvable systems, e.g., a simple pendulum, and irregular or chaotic for complex systems, e.g., weather or superconducting junctions. Dibyendu Roy and collaborator Tomaz Prosen have identified a new mechanism of chaos in a quantum system of a periodically kicked lattice of particles (e.g., electrons) in the presence or absence of a conserved particle number. The spectral form factor (SFF) is an important measure to reveal chaotic behavior in such systems. It characterizes the fluctuations in the density of energy levels of the lattice at high energies. Their study establishes a mapping of the SFF of the quantum system to an average recurrence probability of a classical Markov chain, which is a well-known stochastic model of random events in which the probability of each event depends only on the state attained in the previous event. They have shown the timescale beyond which SFF has a universal form predicted by random matrix theory to be independent of the system size in the absence of particle number conservation, which is natural in superconductors, and it scales quadratically with system size for particle number conservation as in metals and semiconductors.

The motion in classical mechanics can be regular for integrable systems, and irregular or chaotic for nonintegrable systems. Quantum Chaos is a branch of physics that tries to identify and understand the chaotic motion of nonintegrable systems when the quantum effects are significant. One key goal of quantum chaos is to establish a relationship between the universal

spectral fluctuations of chaotic quantum systems and the random matrix theory (RMT). It took significant research efforts spanning over twenty years to obtain such a goal for single-particle systems whose corresponding classical dynamics are fully chaotic. Only recently, a series of studies enabled further progress in establishing such a relationship for low dimensional and locally interacting, nonintegrable many-body systems where local degrees of freedom, e.g., spin-1/2's, fermions, qubits, have no classical limit. These studies have analytically computed the spectral form factor (SFF) characterizing spectral fluctuations at high energies, and the derived SFF shows a good agreement with the RMT.

Unitary symmetries are useful tools in our understanding of quantum dynamics and the RMT symmetry classification. Dibyendu Roy and collaborator Tomaz Prosen made an essential step forward by exploring analytically and numerically the role of unitary symmetry such as particle number conservation on the SFF and Thouless timescale (beyond which SFF has universal RMT form) in a minimal model of spinless fermions and have shown that the SFF in the continuous-time limit can be obtained from a Hamiltonian of an anisotropic and isotropic Heisenberg spin-1/2 chain model with periodic boundary conditions, respectively, in the absence and presence of unitary symmetry. While they find the Thouless time to be independent of the system size for a unitary symmetry breaking model, it scales quadratically with system size for a unitary symmetric model. They also provide exact numerical results for SFF, which are consistent with our theoretical predictions.

The present study extends the recent effort to identify microscopic mechanisms of quantum chaos to a many-body fermionic lattice system with nearest-neighbor hopping processes and long-range pairwise interactions in the presence or absence of conserved particle number. A new dynamical chaos mechanism has been found which maps the SFF to an average recurrence probability of a classical Markov chain with transition probabilities given as square-moduli of hopping amplitudes. The results provide a useful tool to investigate the ergodic phase of long-range interacting systems with disorder which have been investigated in recent years in the context of many-body localization transition. The article is now published: *Physical Review E, 2020, Vol.102, Article No.060202(R).*

[Dibyendu Roy and Tomaz Prosen, University of Ljubljana, Slovenia]

Topological aspects of periodically driven non-Hermitian Su-Schrieffer-Heeger model

Specific quantum systems possess a band-structure topology, which gives rise to robust phenomena like the quantum Hall effect. In a recent work Dibyendu Roy and Vivek Vyas have found that the environmental interactions in innocuous quantum systems can lead to a strange underlying topology, which is also controllable. They studied the celebrated one-dimensional periodic lattice system, the Su-Schrieffer-Heeger model, in the presence of interactions with an environment. The effects of environmental interactions are judiciously accounted to yield a simple yet effective working model. This model's careful analysis shows that the model displays a strange metallic phase, whose topology is akin to a Mobius strip. Interestingly it was found that this topology can be further changed in the presence of an oscillating electromagnetic field by tuning its amplitude and frequency. Apart from the Mobius metallic phase, the model can be adjusted to traverse into the topological insulating phase, wherein the system displays robust edge states.

The existence and consequences of topological quantum numbers in condensed matter systems have been a subject of great interest in the last two decades. The topological aspects of closed quantum systems with Hermitian Hamiltonians have been the main focus for a long time. Of late, the study of topological properties of non-Hermitian Hamiltonians has gained significant attention both in theory and experiments. It is now understood that the topological structure of the non-Hermitian system is much richer and diverse than their Hermitian counterparts. In this context, the concepts

of bulk-boundary correspondence, topological invariants, and geometric phases have been scrutinized in many recent studies.

In condensed matter systems, the bedrock underneath the topological aspects is a discrete spatial translational symmetry in the system, giving rise to the Brillouin zone in the k-space. Interestingly, there is an ingenious way of generalizing the same mathematical structure in the temporal domain by driving the system externally by a periodic potential. Such driving can effectively add another dimension to the spatially periodic lattice; thus, a driven lattice system's topological properties fundamentally differ from the undriven case.

What is the proper topological invariant capturing the topological phases of such a periodically driven non-Hermitian system? Can these phases of the system be probed by tuning the driving potential? These are some questions that immediately arise. In a recent work, Dibyendu Roy and Vivek Vyas studied the topological properties of a non-Hermitian extension of the celebrated Su- Schrieffer-Heeger model driven by an external AC electromagnetic field to answer the above queries (see Figure 1). They found that the bi-orthonormal geometric phase acts as a topological index, well capturing the presence/absence of the zero modes. The model is observed to display trivial and non-trivial insulator phases and a topologically non-trivial Mobius metallic phase. The driving field amplitude is shown to be a control parameter causing topological phase transitions in this model. While the system displays zero modes in the metallic phase apart from the non-trivial insulator phase, the metallic zero modes are not as robust as those found in the insulating phase. They further find that zero modes' energy converges slowly to zero as a function of the number of dimers in the Mobius metallic phase compared to the non-trivial insulating phase.

[Vivek M Vyas and Dibyendu Roy]

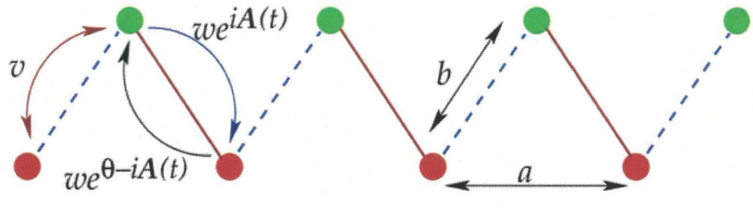


Figure 1. A schematic diagram of the driven one-dimensional periodic lattice. The red and green circles denote two sublattice sites. The lattice constant is a, and two sites in a unit cell are separated by distance b. The intracell hopping amplitude is v, whereas the intercell amplitudes are $we^{iA(t)}$ and $we^{\theta-iA(t)}$ respectively for to and fro tunneling in the presence of a time-periodic vector potential A(t) and a non-Hermiticity measure è. The non-Hermiticity mimics the environmental effect on the lattice. This work has been published in Phys. Rev. B: PhysRevB.103.075441

Interplay of coherence and interaction in light propagation through waveguide QED lattices

Dibyendu Roy and collabortors Tarush Tiwari and Rajeev Singh investigated the role of optical nonlinearity in light propagation through two different waveguide QED lattices, namely a chain of qubits with direct coupling between the nearest neighbors and a chain of connected resonators to each of which a qubit is side-coupled. An efficient truncated Heisenberg-Langevin equations method was applied to show loss of coherent light transmission with increasing intensity in these lattices due to effective photon-photon interactions and related photon blockade mediated by nonlinearity in qubits. In contrast to the direct-coupled qubits, they found a revival in the coherent light transmission in the side-coupled qubits at relatively higher intensities due to saturation of qubits by photons. They further studied these lattices within the quasi-classical approximation, which fails for a broad set of parameters leading them to devise a technique to modify the quasi-classical analysis which gave much better results. Lastly, light propagation in an inhomogeneous lattice of side-coupled qubits was examined and non-monotonicity in light transmission with increasing light intensity was observed.

The physics of mesoscopic collections of quantum particles has been extensively explored in the past for investigating quantum effects such as size confinements, interference, interactions, and band-topology. The quantization of conductances, persistent currents, and Coulomb blockade are well-known examples of quantum effects in lower dimensional systems. Though these phenomena were particularly popular for mesoscopic electrical devices, recent efforts in quantum photonics have also demonstrated many interesting mesoscopic quantum effects in various cavity, circuit and waveguide QED set-ups. Dibyendu Roy and collaborators Tarush Tiwari and Rajeev Singh have studied nonlinear quantum transport of light through one-dimensional (1D) QED lattices connected to radiation fields at the boundaries. In particular, they investigated waveguide QED lattices either (a) in the absence of optical confinement (cavity) along the light propagation direction or (b) when the coupling to and from the cavity(ies) dominate the internal system losses in the so-called overcoupled regime.

The interplay between coherence and interaction has been studied extensively in the context of electron transport in disordered conductors. In the absence of interaction at low temperatures, the phase acquired by the particle along different paths add in a coherent manner and may result in destructive interference for example giving rise to Anderson localization. The effect of nonlinearity caused by interaction among electrons in a disordered conductor can lead to a loss of this coherence which results in an ergodic phase. The photonic systems have their own distinctive features different from electrical devices. Photons being charge-neutral do not interact with each other and can have very long spatial and temporal coherence. An effective interaction between photons can be realized through their coupling to matter. Since the effective interaction is induced by the medium for photons, one also expects such interaction to affect/influence the coherence in photon transmission differently than interaction in electron transport. The present study employs such light-matter coupling to investigate the interplay of coherence and interaction in photons' quantum transport in a 1D mesoscopic array of qubits. This work is available in *arXiv:2010.14935*

[Dibyendu Roy and collaborators Tarush Tiwari and Rajeev Singh from Indian Institute of Technology (Banaras Hindu University)]

Nonequilibrium electrical, thermal and spin transport in open quantum systems of topological superconductors, semiconductors and metals

Nonequilibrium transport in various open quantum systems whose systems and leads/baths are made of topological superconductors (TSs), semiconductors, and metals was studied during the past year by Dibyendu Roy and collaborator Nilanjan Bondyopadhaya. Using quantum Langevin equations and Green's function method, they derived exact expressions for steady-state electrical, thermal, and spin current at the junctions between a system and leads. They validated these current expressions by comparing them with the results from direct time-evolution simulations and then showed how an electrical current injected in TS wires divides into two parts carried by single electronic excitations and Cooper pairs. They further showed ballistic thermal transport in an open TS wire in the topological phase under temperature or voltage bias. The thermal current values grew significantly near the topological phase transition, where thermal conductance displays a sharp quantized peak as predicted earlier. They relate the quantized thermal conductance to the zero-frequency thermoelectric transmission coefficient of the open TS wire. A large thermoelectric current near the topological transition of the TS wires was also observed. The role of superconducting baths in transport is demonstrated by thoroughly examining the features of zero-temperature differential electrical conductance and thermal conductance in open systems with TS baths.

In a recent work, Dibyendu Roy and Nilanjan Bondyopadhaya developed a general framework to study electrical, thermal, and spin transport in open

quantum systems made of topological superconductors, semiconductors, and metals. The method, a generalization of the quantum Langevin equation and Green's function method, was applied to study the steady-state electrical, thermal, and spin current at the junctions between the system and leads. Using this method, many exciting electrical, thermal, and magnetic transport features, such as quantized thermal conductance and differential spin conductance, thermoelectric current near the superconducting wires' topological transition were discovered. The thermal and magnetic transport findings are highly original and timely, and they can have potential applications for detecting the topological phases of matter. The manuscript results are also significant for topological quantum computation with Majorana fermions, and many of these results can be tested within present experimental expertise. This work is available in *arXiv:2010:08336*

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

Non-equilibrium quantum Langevin dynamics of a charged particle in a magnetic field : Response function, position-velocity and velocity autocorrelation functions

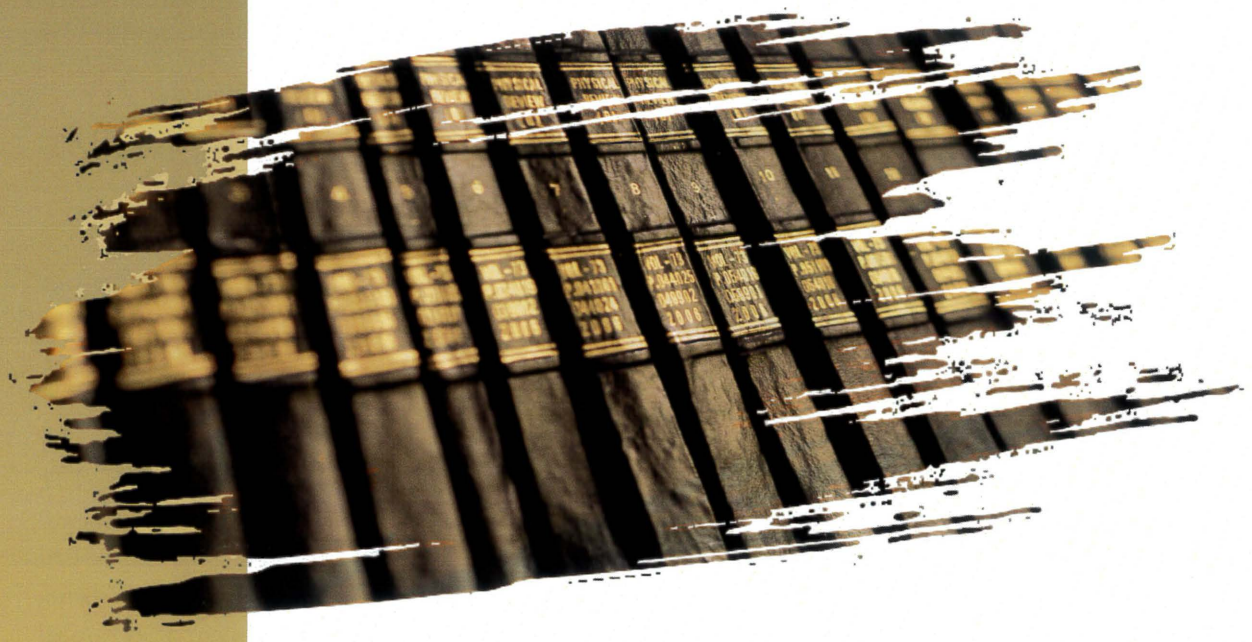
During the past year, Suraka Bhattacharjee and Supurna Sinha along with collaborator Urbashi Satpathi used the Quantum Langevin equation as a starting point to study the response function, the position-velocity correlation function and the velocity autocorrelation function of a charged Quantum Brownian particle in a magnetic field coupled to a bath. They studied two bath models- the Ohmic bath model and the Drude bath model and made a detailed comparison in various time temperature regimes. For both bath models they found a competition between the cyclotron frequency and the viscous damping rate giving rise to a transition from an oscillatory to a monotonic behaviour as the damping rate is increased. In the zero point fluctuation dominated low temperature regime, non-trivial noise correlations led to some interesting features in this transition. They studied the role of the memory time scale which comes into play in the Drude model and studied the effect of this additional time scale. They also discussed the experimental implications of the analysis in the context of experiments in cold ions. This work has been submitted for publication. A preprint is available at *arXiv:2105.07036*

[Suraka Bhattacharjee, Urbashi Satpathi (ICTS) and Supurna Sinha]

Measurements and analysis of response function of cold atoms in optical molasses

Supurna Sinha, along with collaborators Rafael D. Sorkin and Urbashi Satpathi provided theoretical analysis for an experimental effort by Saptarishi Chaudhuri and his group members towards measuring the response function of cold atoms in a 3D optical molasses. The response function of the atomic cloud was measured by applying a pulsed homogeneous magnetic field which provides the perturbing force. They observed an interesting transition from a damped oscillatory to an over-damped behaviour of the response function stemming from a competition between the viscous drag provided by the 3D optical molasses and the restoring force of the Magneto-Optical Trap (MOT). The observations were in good qualitative and quantitative agreement with the predictions of the theoretical model based on the Quantum Langevin equation. They also studied the variation of the Diffusion coefficient of the cold atoms as the atomic cloud is cooled to lower temperatures via sub-Doppler cooling in 3D optical molasses and compared their experimental data with the theoretical calculations using the Stokes-Einstein-Smoluchowski relation. This work has been submitted for publication. A preprint is available at *arXiv:2101.09118*

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



publications

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

For the Astronomy and Astrophysics group, these include Astrophysical Journal, Astrophysical Journal Supplement Series, Astrophysical Journal Letters, Astronomy and Astrophysics, European Physical Journal C, Experimental Astronomy, Galaxies, IEEE Transactions on Antennas and Propagation, IETE Journal of Research, Journal of Astrophysics & Astronomy, Journal of Astronomical Instrumentation, Journal of Cosmology and Astroparticle Physics, Journal of High Energy Astrophysics, Monthly Notices of the Royal Astronomical Society, Nature, New Astronomy and Research in Astronomy and Astrophysics.

The Soft Condensed Matter group has its work published in ACS Applied Nano Materials, ACS Sensors, Acta Biomaterialia, Applied Optics, Bulletin of Materials Science, Colloids and Surfaces A: Physicochemical and Engineering Aspects, Colloids And Surfaces B-Biointerfaces, elife, Interwoven: An Interdisciplinary Journal of Navrachana University, Chemistry Select, Dyes and pigments, Journal of Applicable Chemistry, Journal of Applied Electrochemistry, Journal of Applied Physics, Journal of Chemical Physics, Journal of Materials Chemistry C, Journal of Physical Chemistry Letters, Journal of Molecular Liquids, Journal of Physics: Condensed Matter, Liquid Crystals, Materials Science in Semiconductor Processing, Nano Express, Nanoscale, Nanotechnology, New Journal of Chemistry, Physical Chemistry Chemical Physics, Physical Review E,Physical Review Materials, Physical Review Research, Physics of Fluids, Polymer Journal,RSC Advances, Soft Matter and The Journal of Physical Chemistry Letters.

Publications of the Light and Matter Physics group can be found in ACS Applied Nano Materials, Applied Optics, Applied Physics Letters, Atoms, IEEE Transactions on Instrumentation and Measurement, Journal of Alloys and Compounds, Journal of Applied Physics, Journal of Materials Science : Materials in Electronics, Journal of Molecular Structure, Journal of Optics, Journal of Photochemistry and Photobiology A: Chemistry, Journal of Optical Society of America B, Journal of Materials Science: Materials in Electronics, Nanomaterials, Optical Materials, Optics Express, Optics Letters, OSA Continuuum, Phase Transitions, Physical Review A, Physical Review E and Physical Review Letters.

Theoretical physicists at RRI use journals like Classical and Quantum Gravity, Journal of Statistical Mechanics: Theory and Experiment, Journal of the Optical Society of America B, Physical Review A, Physical Review B, Physical Review E, Physical Review Letters, Universe and others as a medium to share their knowledge with the national and international scientific community.

134 papers with RRI members as authors and/or co-authors were published during 2020-21. There were 6 publications in conference proceedings and 29 publications are in press.

Members of the Institute also regularly publish books and/or articles for popular science magazines to reach out to a wider audience beyond that of specialized technical and scientific journals. During the past year, RRI members wrote 3 book chapters.

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

grants, fellowships and awards

Name	Extramural Grant	Details
Biswajit Paul	ISRO grant for POLIX	Project title: Development of "X-ray Polarimeter experiment (POLIX) Payload" Total grant money: INR 9,50,00,000 Received so far: INR 6,07,56,933 Project start date: September 2017
Urbasi Sinha	ISRO – QKD grant	Project title: Development of a prototype for satellite based secure quantum communication PI: Urbasi Sinha Total grant money: INR 27,00,00,000 Received so far: INR 12,96,21,387 Project started in December 2017
	India Trento Programme of Advanced Research (ITPAR)	Project title: A cheap, light, integrated source for QKD in an integrated photonic circuit PI: Urbasi Sinha Co-PI: Dipankar Home, Guruprasad Kar, Prasanta Panigrahi Total grant money: INR 1,61,13,520 Received so far: INR 57, 03, 520 Project started in February 2019
	DST – QuEST	Project title: Long distance quantum communications: Repeater and Relay technologies PI: Urbasi Sinha Co-PI: Arun K Pati, Ujjwal Sen, Aditi Sen-De Total grant money: INR 2,17, 60, 000 Received so far: INR 1, 52, 84, 000 Project started in April 2019
	MEITY	Project title: Centre for Excellence in Quantum Technology PI (from RRI): Urbasi Sinha Co-PI (from RRI): Saptarishi Chaudhuri, Sadiq Rangwala, Dibyendu Roy Total grant money: INR 10,00,00,000 Received so far: INR 7,76,96,000 Project started in April 2020

Name	Extramural Grant	Details
Gautam Soni	BDTD/08/2019	Prototype for electronic mass screening device for Point-of-Care diagnostic of Sickle Cell Diseases Total grant money: INR 46,49,000 Received so far: INR 33,14,000
Pramod Pullarkat	BT/PR23724/BRB/10/1606/2017	Project title: Mechanobiology of cell adhesion under dynamic shear. PI – Namrata Gundiah (IISc, Bangalore), CoPI's – Pramod Pullarkat, Gautam Menon (IMSc, Chennai) Duration: starting from 17-05-2018 for three years Total amount: 95.884 lakhs Received so far: 20,57,000 DBT-Welcome, TeamScience Grant PI: Pramod Pullarkat, Aurnab Ghose (IISER-Pune) and Carsten Janke (Institut Curie, Paris) Total amount: INR 10,00,00,0000
Ranjini Bandyopadhyay	DST-SERB Grant EMR/2016/006757	Project title: Understanding the jamming dynamics and nonlinear viscoelasticity of non-equilibrium viscous liquids with non-linear dielectric and rheo-dielectric studies". Co-PI: Paramesh Gadige, c SSIHL, Andhra Pradesh Total amount: INR 47,40,000 Received so far: INR 23,96,500 Project started in 2019
Saurabh Singh, Mayuri S Rao, Jishnu Nambissan	ISRO Grant-in-Aid	Project Title: Pre-project activities for PRATUSH (Probing ReionizATion of the Universe using Signal from Hydrogen) PIs: Saurabh Singh (RRI, McGill University), Mayuri S. Rao (RRI) and Jishnu Nambissan T. (RRI) Grant Amount: INR 56,06,000 Received so far: INR 36,00,000 Start date: March 13, 2019
Reji Philip	SERB – TARE Program	Project title: Femtosecond Laser-Induced Breakdown Spectroscopy (fs-LIBS) for Multi-elemental Compositional Analysis Mentor: Reji Philip Teachers Associate: Anoop KK Start Date: 26.11.2018 Total amount: INR 18,30,000 RRI share: INR 3,35,000
Sanjukta Roy	DST - Women in Science	Funds Received: INR 18,38,500

Name	Fellowship	Details
Dibyendu Roy	SERB-Ramanujan Fellowship	Start Date: 18.1.2016 Received so far: INR 62,60,000 Duration: 5 years
Sumati Surya	Visiting Fellowship, Perimeter Institute	This Fellowship will fund multiple visits to Perimeter Institute for a period of three years starting in 2019
Urbasi Sinha	Simons Emmy Noether Fellowship	This Fellowship will fund visits to Perimeter Institute for a duration of upto one year
Sayantan Majumdar	SERB Ramanujan Fellowship	Total research grant amount: INR 38,00,000 Start Date: May 2018 Received so far: INR 22,80,000 Duration: 5 years
E Krishnakumar	Raja Ramanna Fellowship	Total Fellowship Amount: 40,50,000 Received so far: 25,50,000 Duration: 3 years
Urna Basu	SERB Ramanujan Fellowship	Total research grant amount: INR 38,00,000 Received so far: INR 7,60,000 Duration: 5 years

Sourav Chatterjee and Urbasi Sinha
Two member team of Sourav Chatterjee and Urbasi Sinha won the BRICS Future Skills Challenge on Quantum Technologies 2020, a part of the WorldSkills Competition.

Sadiq Rangwala
Sadiq Rangwala (LAMP) has been elected Fellow of the Indian Academy of Science.

Ravi Subrahmanyan
Ravi Subrahmanyan (Emeritus Professor) has been selected for the IIT Madras Distinguished Alumnus Award 2021.

Dibyendu Roy
Dibyendu Roy (TP) has received the Abdus Salam International Centre for Theoretical Physics (ICTP) prize for 2020 for his outstanding and original contributions to Condensed Matter Physics.

Urbasi Sinha
Urbasi Sinha's (LAMP) research received recent international acclaim as the only work from India to be highlighted in Physics and Mathematics research in Asia over the last five years by the Asian Scientist magazine. Her research was also recognized by the Department of Science and Technology as one of 20 major success stories of 2020.

Electronics Engineering Group

The Electronics Engineering Group (EEG) has been extensively involved in supporting engineering requirements of experimental activities of scientific groups at the Institute. Over the past several decades, engineers and technical staff of the group have built hardware and developed software for applications in experimental radio astronomy, biophysics, light and matter physics and X-ray astronomy. Staff have also gained, over years, expertise in building specialized equipments which could be flown to space. EEG has played a major role in the success of several national and international projects like Ooty Radio Telescope, Giant Metre Wave Radio Telescope, Murchinson Widefield Array and Shaped Antenna measurement of the background RAdio Spectrum (SARAS). The group has expertise in diversified fields like antenna, RF and Microwave circuits, digital signal processing, high speed digital circuits, and firmware development for FPGAs and software for data analysis. EEG at present is working on next generation of devices like Radio Frequency System-on-Chip (RFSoC), Graphics Processing Units (GPU) and trying to develop boards using them. These will be versatile and generic in nature useable for different applications. In addition, the group will also be working on designing frequency independent antennas over bandwidths spanning more than just one octave. For the past several years, EEG has been supporting projects like POLIX (X-ray polarimeter), Epoch of Reionization and Brain Computer Interface, among others.

Antenna design for space application

Detecting the Cosmic Dawn (CD) signal in the presence of foreground radiation signal - orders of magnitude brighter than the former, is an engineering challenge. It is expected to carry information about the thermal history of the early Universe. The detection requires the antenna to meet stringent requirements of having monotonic spectral characteristics both in its impedance and radiation characteristics and minimum dispersion in its radiation patterns as a function of frequency, for separating out the desired signal from the total sky signal measured. Any ground based experiment conducted for the detection of CD signal, is limited in achievable sensitivity by the undesired noise contribution from the surrounding medium like real earth and its variation with frequency and more importantly man-made interference. This can be overcome significantly if the experiment is carried out in space. However other constraints which are of less importance on ground like mass, deployability and maximum physical dimension play major roles in the antenna design. Considering these, designing an antenna for the stated application is challenging. Many properties of antenna and their dependence on the surrounding media need to explored extensively before arriving at a compact light weight radiating structure. With a fair amount of understanding of the electromagnetic behaviour of the antenna with the surrounding medium, a log spiral reflector based conical monopole antenna has been designed to operate in the frequency range 55-110 MHz. The structure has been optimized in CST Microwave electromagnetic simulation software while meeting monotonicity in its spectral response and minimum variation of antenna gain over the band of interest. The simulated structure and its physical dimensions are shown in Figures 1-2. The satellite bus which is a mechanical structure used to mount and house all flight related subsystems including antenna and its related electronics is incorporated below antenna reflector. It has a dimension of about 40cm x 40cm x 60cm.

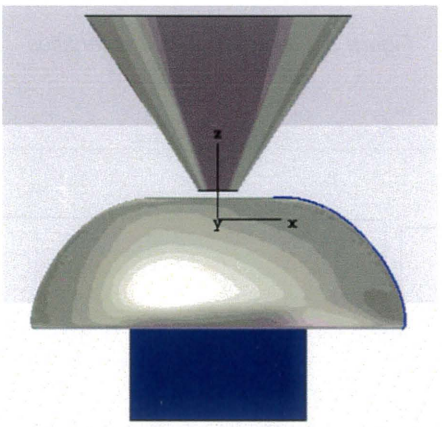


Figure 1. Photograph of the log spiral profiled reflector based monopole conical antenna.

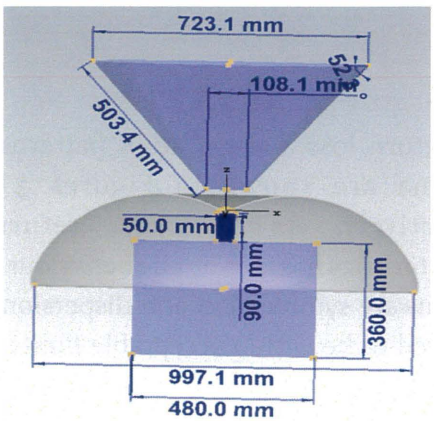


Figure 2. Optimized physical dimensions of the antenna simulated in CST Microwave electromagnetic software.

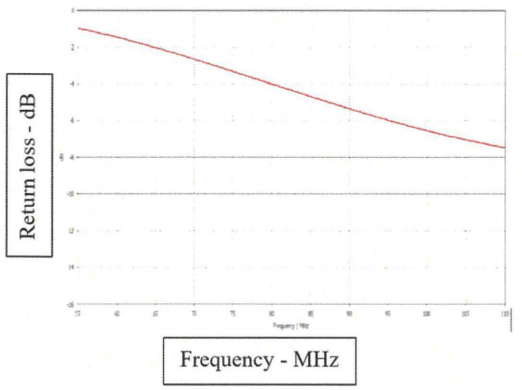


Figure 3. Return loss characteristics of the antenna.

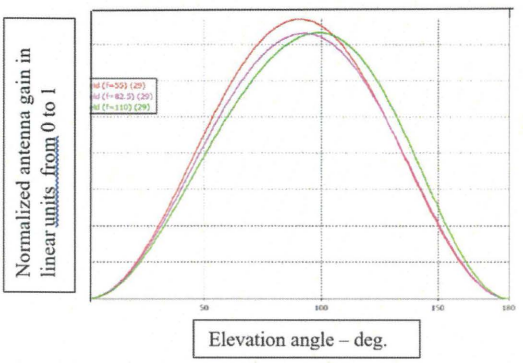


Figure 4. Radiation patterns of the antenna at 55,82.5,110 MHz

The return loss and radiation patterns of the antenna are shown in Figures 3 and 4 respectively. As observed, return loss characteristics has monotonic behaviour and the patterns are symmetrical and dispersion seen is observed to be within acceptable limits.

Lightweight compact Faraday cage with high shielding efficiency for space application

Light weight and compact Faraday cage with a good shielding effectiveness (at least > 70 dB at frequencies less than 50 MHz) is an absolute necessity for launching a radio receiver into space. This is to ensure that the self-generated digital noise itself does not limit the sensitivity of the receiver. Based on NASA reports, a compact and light weight faraday cage is being developed to house the radio receiver that will detect Cosmic Dawn signal in the frequency range 50-200 MHz, which in principle, can be used to house digital electronics provided it has desired shielding effectiveness. The new faraday cage being built in RRI is made out of carbon cloth and resin instead of metal to reduce overall weight and achieve rigidity. A metal woven cloth instead of metal is used for radiation shielding. A prototype box having

Figure 5. Resin, carbon cloth and conductive cloth based light weight faraday cage.

Figure 6. RFSoC ZCU111 evaluation board.

dimensions 200mm x 300mm x 400mm has been built and is being evaluated. Initial measurements indicate that the shielding effectiveness is about 35 dB at 50 MHz. It is proposed to improve it by i) making a warp free top plate, ii) using RFI gasket made out of metal woven cloth. The achieved reduced weight of the faraday cage is as low as 3.5 kg compared to about 20 kgs when the same is made out of stainless steel.

Adopting latest technology in digital board design

EEG is working towards realizing a compact power-efficient digital correlation spectrometer using Radio Frequency System-on-Chip (RFSoC) which integrates RF-class analog technology with FPGAs providing system benefits like direct RF sampling of multiple signals and reduced power. The RFSoC ZCU111 based evaluation board with which EEG is working is shown in Figure 6. Integrated prototype card which is a novel hardware platform for digital signal processing and acceleration is being designed and developed using RFSoC. This development is considered as an important activity undertaken by RRI under bridging phase of the Square kilometre Array (SKA). In addition, high performance computing algorithm is being developed for central signal processing pulsar search sub-element of SKA.

Brain computer interface system for patients with impaired movements

An in-house simple, cost effective brain computer interface system for paralysed patients is being developed at the Electronics Engineering group. The system assists patients with their communication and movements. Steady State Visually Evoked Potentials (SSVEP) available on the patient's scalp are used to perform the above operations. Trials on healthy subjects are being undertaken in some of the hospitals identified to evaluate the system being built. New methods of data analysis are being investigated. Exploring non-contact electrodes to pick up EEG signal is also being considered. New methods of data analysis are being investigated.

X-ray telescope in space : For studying the polarization of X-rays from cosmic sources

This space-based telescope also known as Polarimeter Instrument in X-rays (POLIX) being built at RRI is capable of measuring the polarization of X-rays of cosmic sources in the energy band 5-30 KeV. EEG staff have been working hard on both qualification model (QM) as well as flight model (FM) of various components of the telescope subjecting them to various tests at URSC, ISRO, Bangalore. In the qualification model, one working detector module along with all mechanical components were assembled and successfully subjected to vibration tests at qualification level at URSC, ISRO. All PCBs of two Backend Electronics (BE) and two BE packages have been assembled and tested successfully with the detectors and ground checkout system. The BE packages have also been successfully subjected to qualification level vibration tests at URSC-ISRO. In the flight Model (FM), assembly and tests have been carried out for three out of four FM detectors including their leak tests on the detector housings. Significant progress has also been made in the assembly of Backend Electronics PCBs.

EEG's contribution to outreach programmes of the Institute

EEG has always participated very actively in educating students of school and colleges on several occasions like Institute's open day celebration, during regular visits arranged by academic institutes and under visiting student's programme (VSP). Students are also given opportunities to take part in the on-going research activities and get hands on experience both in theoretical and practical aspects.

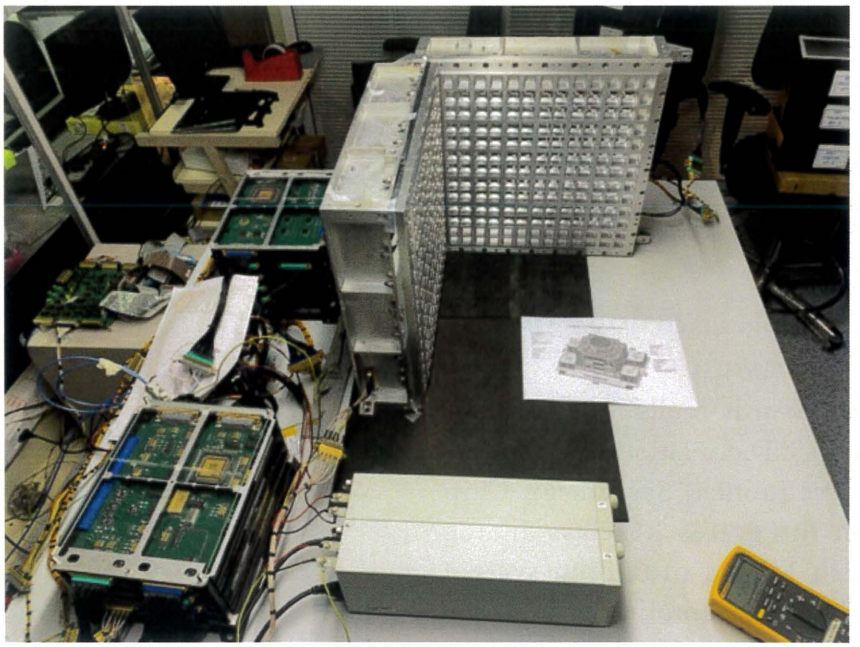


Figure 7. QM Detectors with backend electronics test setup

Mechanical Engineering Services

Mechanical engineering services (MES) is a diverse and versatile department consisting of 4 sections - Basement workshop, Sheet metal workshop, Painting section and Carpentry section. MES plays key roles in a wide range of activities at the Institute ranging from Interior wooden/metal furnishing to manufacturing of precision components for experimental science and CNC machined components used as critical flight hardware in payloads for space launch. The group has a qualified and skilled team working in unison. The group is equipped with modern CNC machines and CAD-CAM software which helps at visualization of final product and also reduces considerable number of iteration before final product is manufactured to specification.

Following are few brief descriptions of activities undertaken by MES during 2020-21.

Figure 8. Top panel: MES members assembling the telescope structure. Bottom panel (from left): Laser collimation tube mounted on a telescope stand, device for single ion trap, gas filling port tool.

- **External-Cavity Diode Laser Setup**
  Fabricated anexternal-cavity diode laser setup via CNC machining using a combination of materials such as Aluminium for external enclosure, Stainless steel (SS304) for housing laser diode, grating, piezo actuator and mirror. Brass disk was machined and used for rotary parts where it acts as a sliding medium.

- **Laser Collimation Tube Setup**
  For use in the experiment on Quantum Communication using photons, MES fabricated a laser collimation tube. It is fitted with lens at both ends with provisions for easy adjustment of focal distance.

- **Backup Structure for Efficient Linear Array Imager Telescope**
  The RRI Efficient Linear Array Imager telescope is under construction at the Gauribidanur Field Station. MES contributed towards welding and assembling the structure.

- **Single Ion Trap for Use in the Quantum Interactions Lab**
  Fabricated a single ion trap.It is worth noting that while fabricating this structure we had to adhere to stringent requirement of surface topography and alignment.

- **Gas Filling Port Tool for Use in X-ray Astronomy Lab**
  Agas filling port for X-ray detector housing was fabricated by MES. This tool is used to fill Zenon gas in X-ray detector housing without leak. Once the gas is filled using this tool one can lock the filling cap of the X-ray detector housing.

Computer Group

The Computer group manages and maintains the IT infrastructure in the Institute and handles and supports various computing needs of the research groups and other departments. The computer group undertook a few activities apart from routine work. Due to COVID-19 pandemic staff and students started working from home. To enable virtual interactions among RRI members and collaborators Zoom license was purchased for the video conferencing. A video conferencing portal using open source software Jitsi was also set up. Scheduling of conferences, online meetings/talks was also done during and after the lockdown. Access to the e-Journals and computing resources from outside RRI and home was also provided.

Online forms were created for Estate/Civil/ Electrical work request and Purchase Requisition to reduce paper work. Medical Referral letters were digitised enabling easier and faster issuing. Collaboration softwares Jira and Confluence were installed for use by the EEG group. The Digital Repository software DSpace and the Library Management Server software KOHA were upgraded to the latest version. Dropbox like facility using OwnCloud was installed for two labs and the Accounts department for storing data, files and documents.

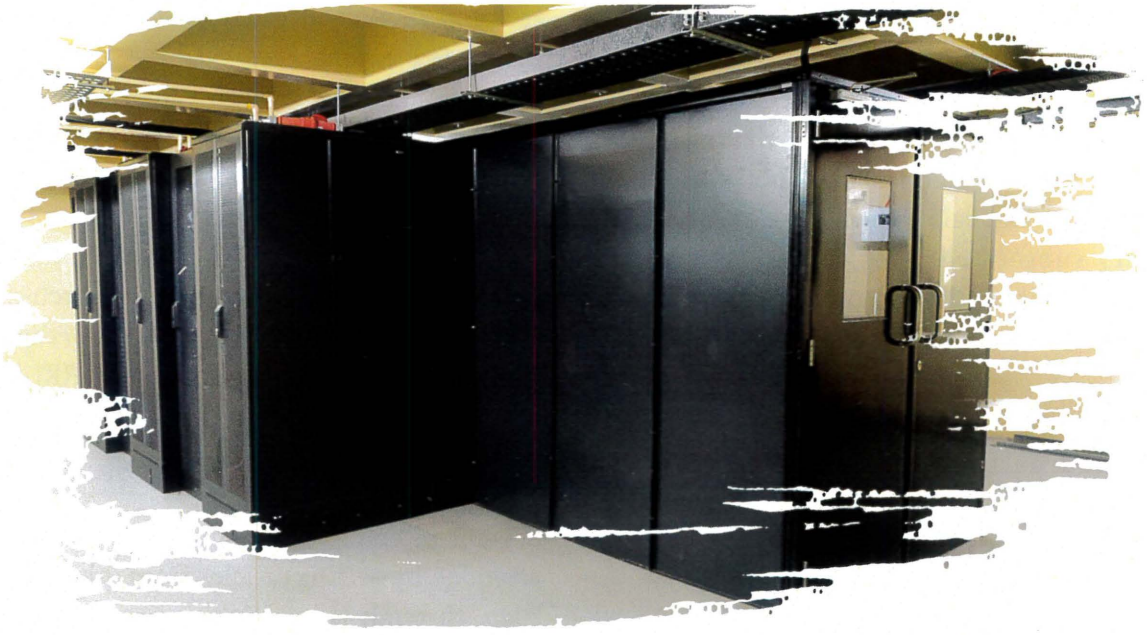
The group was involved in the PhD admission process via the following: hosting the online application portal, application data collection, creating online form for Letter of Reference, sending emails for recommendation and call letters, scheduling on-line interviews and setting up a portal for uploading of shortlisted students' data for the interview committee members to access during the interview.

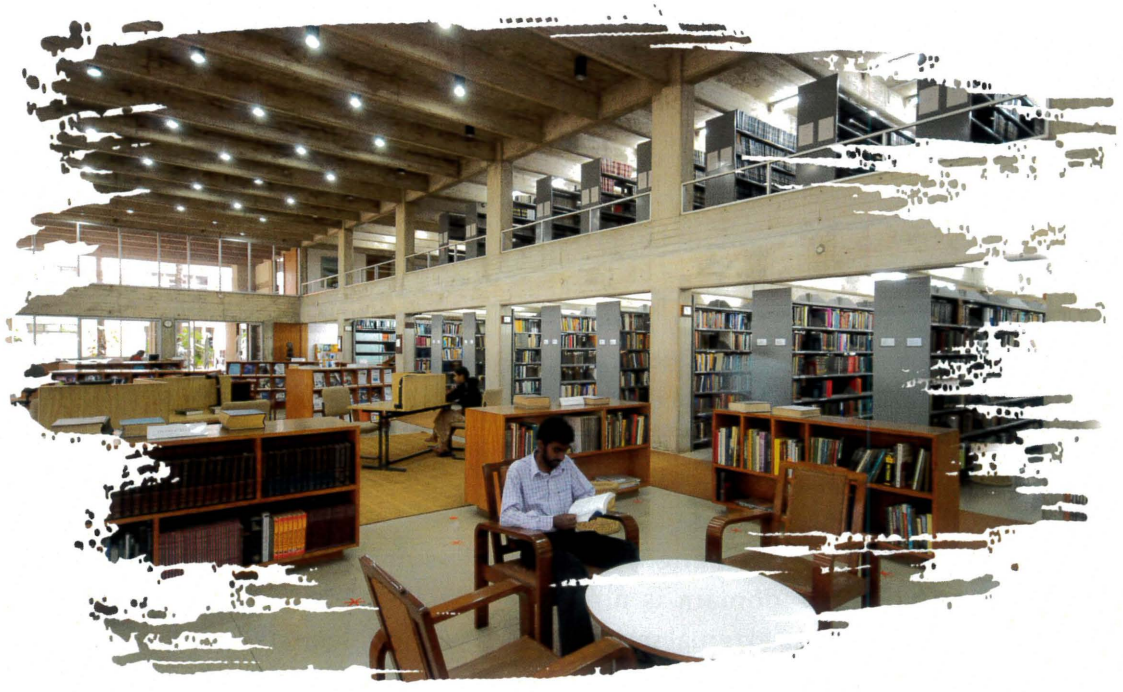
Network connectivity was extended to the three new QKD labs and two security cabins. 512-core High Performance Cluster with two large memory (1TB) nodes was procured and installed in the new Data Center. A 120KVA Modular UPS for the new Data Center was commissioned and installed. The NKN internet link, network equipment and all the servers were shifted and installed in a phased manner in the Data Center. The Data Center is now completely operational.

A new DNS server for the LAN was installed and configured. The domain 'rri.local.net' was discontinued and 'rri.res.in' domain is now being used for both internal and external servers for uniformity. The file server (NFS) and proxy server were also upgraded. A Linux server was set up for the Canteen Management System to facilitate contactless payment using smart card. Installed Overleaf application in a Linux server for online LaTeX document collaboration. This year's PhD online application is being developed and implemented using NoPaperForms – a Software-As-A-Service platform.

The acoustics in the Video Conference room in the Library was looked into and it was suggested to carpet the floor and install full-length curtains to reduce the echoing in the room. It was completed and the quality of audio and sound has improved drastically.

Wireless network survey was conducted in all the buildings to identify the wireless network coverage problem and the location of wireless access points. It is planned to upgrade the network switches and the wireless network to WiFi-6 - the next generation WiFi. This will improve the speed, coverage and connectivity to the LAN.





Library

The RRI Library, founded by Sir C V Raman in 1948, started functioning with his personal collection of books and journals. The library has both print and electronic information resources. The library caters to both general and specialized information needs of its users. Currently, the library has a total collection of 71185 comprising of books and bound volumes of journals. Out of this, 29500 are books, and 41685 are bound volumes of journals. During the past year, the library subscribed to 15 e-journals, 30 print journals. Library has a total of 670 non-book materials.

Library activities during 2020-21

Renewed partnership of RRI Library with National Knowledge Resource Consortium through which library users can access 4600 published journals. RRI library is a content partner to the National Digital Library of India project of IIT Kharagpur. The research output of RRI is hosted on https://ndl.iitkgp.ac.in/, which acts as a single window to the nation's scholarship. Library streamlined the recommendation of journals through an online structured questionnaire seeking approval for renewal or discontinuation of journals. As a result, few journals were added and few were discontinued. Library web page is continuously monitored to keep it updated and provide access to both subscribed and open-source content of research interest. Library conducted plagiarism check of 12 PhD theses submitted by RRI students in addition to 50 research papers and few dissertations. Researcher ID of the entire faculty was updated regularly. The RRI library handled article processing charges of 11 research papers.

Several Inter Library Loan (ILL) requests were attended by getting articles from other libraries. Also, through ILL, articles were sent to other libraries. Grammarly software to aid writing skills has been renewed for the current year.

Stock verification of books has been done and books found missing is being traced. During the past year, students and faculty routinely used library video conference room for discussions, PhD defence, and Zoom meetings.

Another major project accomplished during this period was Raman Research Institute archival gallery. This photo gallery consists of milestones from Sir C V Raman's era and current research. Now this is made available for public viewing.

Library automation and Digital Library -The RRI library had migrated completely to KOHA an open-source Library software. This year the software has been upgraded to version 20.5. Raman Research Institute Digital Repository also known as e-Sangrah is an active repository of a variety of information related to the Institute. The digital repository software DSpace has been upgraded to version 6.3. Scholarly publications are uploaded regularly. Number of uploads during 2020-21 were 350. Theses submitted by RRI students were also uploaded to the repository. The total records on RRI Digital Repository currently stands at 11000. "Imprints-collection," an offshoot of RRI digital repository, continues to thrive with regularly updated information. This bio-bibliographic database currently has 43 profiles including 5 profiles of those scientists who have left RRI to pursue assignments elsewhere. In addition, digitization of archival materials, photographs, and audio/video continued during the past year.

Other Events

1. The library had a themed display of books to commemorate two occasions: our Independence Day and Sir Roger Penrose winning the Nobel Prize.

2. Library orientation was done for 2020-21 batch of PhD students

knowledge communication

PhD Programme

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

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

During 2020-21, 90students from all over India were enrolled in the PhD programme and conducted research with scientific staff members from the four broad research groups at the Institute.

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

Name	Thesis Title
Sreeja Sasidharan	Influence of some bioactive molecules on the structure and phase behaviour of lipid membranes
Deepshika Malkar	Investigations on molecular organization and physical properties of asymmetric bent-core liquid crystals
Aditi Vijayan (JAP)	Understanding multi-wavelength signatures of galactic outflows through 3-D simulations
Saikat Das	Origin and propagation of high energy cosmic ray particles
Nomaan X	Aspects of quantum fields on casual sets
Akash Kumar Patwa	Detecting the 21 cm signal from the Epoch of Reionization using drift scans

Nine PhD theses were awarded:

Sushil Dubey	Mechanical responses of neuronal cells and spider silk
Simanraj Sadana	A fresh look at Classical Theory of Light with applications to quantum interferometry
Varun	Understanding the magnetic field configuration in X-ray pulsars through spectroscopy and polarimetry
Karamveer Kaur	Dynamics and statistical mechanics of Keplerian stellar systems
Meera Thomas	Surfactant-polyelectrolyte complexes: Structure and interactions
Raj Prince	Multi-wavelength data analysis and theoretical modeling of blazar flares
Deb Sankar Banerjee	Active hydrodynamics of actomyosin elastomer with turnover during tissue remodeling
Sanjay Kumar Behera	An experimental study of the kinetically arrested states of colloidal suspensions
Swamynathan K	Synthesis and characterization of some discotic amphiphiles

Postdoctoral Fellowship Programme

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

Candidates who have at least one year of experience as a postdoctoral researcher and have a proven track record of being able to conduct original and independent research can apply for a limited number of Pancharatnam Fellowships offered at RRI. Here too, applications are accepted throughout the year and the processing takes about 4 to 6 months. The fellowship is for 2+1 years. Further details about the Postdoctoral and Pancharatnam Fellowships can be found on the RRI website.

During the year 2020-21 there were 18 Postdoctoral and Pancharatnam Fellows at RRI.

Research Assistants Programme

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

During the year of this report, 23 personnel were involved in research activities via the Research Assistants programme.

Visiting Student Programme (VSP)

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

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

During the year 2020-21, 18 students availed of this programme. A complete list of VSP students who interned at the Institute during the year is given in Appendix VI.

Conferences

Institute members visit various other institutions in India as well as overseas to attend conferences and workshops. These events play an important role in providing an opportunity to exchange ideas with the scientific community at large and thus set the stage for future collaborations with researchers from other institutions. In addition, scientific staff members gave lectures and invited talks at a variety of workshops, international conferences, multinational project meetings and training programmes. As a part of the outreach activities of RRI, members also visited colleges around the country and organized special workshops on different research topics, delivering lectures, talks and presentations.

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

Seminars and Colloquia

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

The Thursday colloquium is an event held at the Institute to promote further interaction not only between the various research groups within RRI but also between RRI and the invited speaker and his or her affiliated institution. The colloquium aims to cover emerging science topics and bring an interdisciplinary flavour to the event by introducing themes from various other disciplines to the members of the RRI community.

During the past year, RRI invited speakers from all over India and the world to deliver the seminars and colloquia. A complete list of speakers and the diverse topics presented is given in Appendix III.

Visiting Scholars

With an aim to further augment the interaction between the members of the Institute and scholars belonging to other institutions, RRI actively encourages visits from a large number of scientists, researchers and engineers. These scholars visit the Institute and contribute new ideas and skills while also benefiting from the expertise of RRI's own members. Visits at RRI can last from a few days to a few months and often lead to fruitful collaborations and conceptualization of new, interesting projects for the Institute.

The pandemic resulted in a limited number of visits by national and international peers. A list of all visitors, where they came from and when they visited RRI can be found in Appendix IV.

Science Forum

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

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

Typically, as part of the RRI Science Forum, papers with exciting new results that are often considered landmarks in that particular field are presented to a wider and more general audience. Based on the presentation, informal discussions, questions and demonstrations are strongly encouraged leading to a better understanding of the underlying concepts of the work presented. This in turn often results in new ideas and new research problems for the members of the RRI scientific community to work on. Owing to the ongoing pandemic the Forum could not take place during the past year.

extramural activities

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

RRI at the India International Science Festival, 2020

The fifth edition of the India International Science Festival (IISF, 2020) jointly organised by the Ministry of Science and Technology and Ministry of Earth Science and Vijnana Bharati was held virtually between22nd and 25thDecember 2020. RRI has been participating in this mega event every year since 2016 by setting up pavilions that showcases the current research areas and research highlights from the past year. The 2020virtual pavilion contained content in the form of panels, audio/video content including science demonstrations prepared such that it was easily understandable by the general public. RRI members Ritu Nehra, Suraka Bhattacharjee and Hemanth M represented the Institute and interacted with the visitors. The pavilion displayed a nice blend of panels on: the Institute, its research activities and interesting panels highlighting the life and science of the Institute's founder Sir C V Raman that were freely accessible to the general public. The pavilion also displayed videos containing many interesting science demonstrations that explain the basic science behind many of the research activities at the Institute. IISF served as a platform for meaningful interactions and exchange of ideas between RRI representatives and the wider society.

RRI in the media

The professional pursuit of science may be a relatively personal enterprise, or a joint activity of a few scientists collaborating with each other towards a common goal, or an enterprise involving hundreds and even thousands of scientists who may be distributed worldwide. Any insight gained or phenomena discovered are then communicated in the form of publications that are intended mainly for fellow scientists. On the other end of the spectrum is the general public whose money more often than not enables these scientific pursuits, but are none the wiser for it. Human beings have this innate curiosity to know and understand the natural world they live in and it would ultimately serve science well to kindle this curiosity, particularly in impressionable young minds. Whatever be the reason, communication of "hi-fi" scientific research couched in language that is easily understandable to one and all is highly desired. Additionally, these popular science articles, snippets and news needs to be disseminated in such a way as to have maximum outreach. The Raman Research Institute is attempting to bridge this gap by posting general write-ups based on research publications by RRI research staffs and students on Facebook, Twitter and blogposts. During 2017-18, RRI continued its commitment to research communication by launching the official RRI YouTube channel. The channel playlists contain lectures, talks, workshops, student and postdoc videos, and archival videos. Along with adding new playlists, existing playlists will be periodically updated with new videos.Between April 1st 2020 and March 31st 2021 there have been 40 facebook posts, 60 tweets and 15 blog posts. Many of our posts and tweets have been liked and retweeted by DST from their official Facebook and Twitter pages.

We now have upwards of 8070 people following us on Facebook and 5311 people on twitter reading and commenting on our posts. The RRI YouTube channel was launched on 16 March 2018. Since then the channel has grown to include 16 playlists with 153 videos that are open for public viewing.

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

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

Official Language Activities

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

The following activities were undertaken during the year under report.

- General orders, Notices, Advertisement, Press releases / Notings, Contracts, Tender forms and Tender notices were brought out bilingually. Section 3(3) of the OL Act was fully complied with.
- Letters received in Hindi were replied to in Hindi.
- Hindi Version of the Institute's website was updated periodically.
- All forms and Standard Formats being used in the Institute were made bilingual.
- The Quarterly Progress Reports regarding progressive use of Hindi are being sent to the Ministry of Science and Technology, Regional Implementation Office and the Town Official Language Implementation Committee periodically.
- The Annual Report has been published both in English and Hindi versions.

- Hindi workshops were conducted periodically and Lectures were delivered by experts on (a) "Diabetes, Hypertension and Obesity - a progressive approach" (b) "How to accelerate the progressive use of Hindi in day to day official work to bring an effective implementation of Official Language policy?" during these workshops. In addition to this, Table workshops and Internal Inspections were conducted regularly for all the Departments.

- Meetings of the Official Language Implementation Committee were conducted periodically with specific agendas. Concrete actions on the decisions taken in the meeting was ensured.

- The Institute actively participated in the Town official language implementation committee meetings conducted during the year.

- Quote of the day and Word of the day in English with its Hindi equivalent were displayed on the bulletin board daily across the Institute.

- Ten phrases in English with its Hindi equivalents were displayed on the main bulletin boards every month for use by officials.

Others

During 2020-21, RRI organized virtual meetings and workshops described in detail under the section titled "Events". Other events include high teas on superannuation of regular staff, sports tournaments, concerts and a variety of cultural programs, both with invited performers and RRI members themselves. Owing to the ongoing pandemic these events were hosted online.

Workshop on Secure Quantum Communications, quantum sensing and metrology

The Institute hosted a 2-day online workshop on the 17th and 18th of August 2020 on recent trends and developments in secure quantum communications as well as quantum sensing and metrology. This is the first event that has been organised by the RRI wing of the newly formed "Center for Excellence in Quantum Technology". The workshop featured talks by national and international experts in the domain with intensive discussions on the state-of-the-art. There were also focused panel discussions on both days featuring eminent scientists, wherein deliberations were done on the possible future research directions in the domains of quantum communications, quantum sensing and metrology. For more details on the Center visit http://rri.res.in/ceqt.html.

Bangalore School on Statistical Physics-XI

The Bangalore school on statistical Physics-XI was conducted between 29th June to 10th July via online lectures. This is the eleventh in the yearly series of lectures organised jointly by Sanjib Sabhapandit from RRI and Abhishek Dhar from ICTS-TIFR, Bangalore. This is a pedagogical school, aimed at bridging the gap between masters-level courses and topics in statistical physics at the frontline of current research. It is intended for Ph.D. students, post-doctoral fellows and interested faculty members at the college and university level. The school included courses on nonequilibrium response theory, topology in statistical physics, statistical mechanics of developed turbulence and Statistical physics of rare events and large deviations.

Visit by Brazilian Delegation

A delegation led by Brazil's Minister of Science, Technology and Innovation H.E. Mr. Marcos Pontes visited RRI on the 26th of February. The delegation visited the X-ray Astronomy and the Quantum Information and Computing laboratories. Biswajit Paul, Vikram Rana and P V Rishin spoke to the visitors about the Institute's efforts towards developing an X-ray polarimeter (POLIX) while Urbasi Sinha spoke about efforts towards secure quantum communications. The aim of the visit was to explore common research interests and avenues for future collaboration between India and Brazil.

Brazil's Minister of Science, Technology and Innovation and his delegation at the Institute

campus

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

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

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

The Guesthouse on campus is equipped with rooms blending modernity with ethnic elegance to comfortably accommodate distinguished visitors and visiting academics including visiting doctoral students. The Canteen on campus provides meals to all guests together with lunch and refreshments to all members of the Institute and also those who work at the Indian Academy of Sciences, which is also located in a corner of the campus. Informal meetings, gatherings, concerts and dinners are usually organized at the "Village" – an ethnically designed area near the Canteen which provides a warm, rustic touch to the overall atmosphere on campus, or on the terrace of the Library building that is in the canopy.

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

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Soft Condensed Matter

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publications

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Shaw, A W; Heinke, C O; Rana, V; +11 Co-Authors
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88. Comprehensive broadband study of accreting neutron stars with Suzaku: Is there a bi-modality in the X-ray spectrum?
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90. Fingerprinting branches on supercoiled plasmid DNA using quartz nanocapillaries
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Optical Materials, 2021, Vol.112, p110804

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Kumar, Ajay; Kumar, Rajeev; Verma, Nancy; Philip, Reji +3 Co-Authors
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John, Jerin Susan; Joy, Nithin; Philip, Reji +3 Co-Authors
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Vaity Pravin; Sagar, Rishav; Dharmadhikari, J A +3 Co-Authors
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107. Measurement of collisions between laser-cooled cesium atoms and trapped cesium ions
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108. Dynamics of mode-locked nanolasers based on Hermite-Gaussian modes
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112. Active velocity processes with suprathermal stationary distributions and long-time tails
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Madhusudana, N V
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114. Observation of ion acceleration in nanosecond laser generated plasma on a nickel thin film under rear ablation geometry
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115. Active Brownian motion in two dimensions under stochastic resetting
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116. Magnified charge carrier conduction, permittivity, and mesomorphic properties of columnar structure of a room temperature discotic liquid crystalline material due to the dispersion of low concentration ferroelectric nanoparticles
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4. Obituary: Hema Ramachandran (1962–2020)
Narayanan, Andal; Nityananda, R
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5. Of light and shadows; Raychaudhuri's equation, the Big Bang and Black Holes
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Niranjan, M; Anand Prakash; Rangwala, S A
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2. PeV-EeV neutrinos from gamma-ray blazars due to ultrahigh energy cosmic-ray propagation
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3. Comparing the inner and outer star forming complexes in the nearby spiral galaxies NGC 628, NGC 5457 and NGC 6946 using UV observations
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Astrophysical Journal, 2021, Vol.914, Article No.54

4. Entanglement entropy of causal set de Sitter horizons
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6. Design and synthesis of extended pyrene based discotic liquid crystalline dyes is published in Dyes
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13. Effect of Fe doping on the structural, morphological, optical, magnetic and dielectric properties of $BaSnO_3$
Sridharan, Kishore; Roy, Nivya; Philip, Reji and Park, Tae Joo
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15. Vibrational spectra, linear and nonlinear optical investigations on 3 chloro 4-fluoro aniline and 2-iodo aniline for optical limiting applications
George, Merin; Sajan, D; Sankar, Pranitha; Philip, Reji
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16. Imidazole and benzoimidazole derived new ionic liquid crystal compounds: synthesis, characterisation, mesomorphic properties and DFT computations
Abdul Karim-Talaq Mohammad*; Omar S Khalefa; Srinivasa H T; Wissam Ahmed Ameen
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17. Tracing the evolution of ultraluminous infrared galaxies into radio galaxies with low frequency radio observations
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20. Fabrication of silver-decorated graphene oxide nanohybrids via pulsed laser ablation with excellent antimicrobial and optical limiting performance
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25. Transmission in a Fano-Anderson chain with a topological defect
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26. pinta: The uGMRT data processing pipeline for the Indian Pulsar Timing Array
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Scheff, Danielle R; Redford, Steven A; Lorpaiboon, Chatipat; Majumdar, Sayantan; R Aaron Dinner; Gardel, Margaret L
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28. Strain localization and yielding dynamics in disordered collagen networks
Bakshi, Swarnadeep; V M Vaisakh; Sarkar, Ritwick; Majumdar, Sayantan
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29. Loophole free interferometric test of macrorealism using heralded single photons
Joarder, K; Saha, D; Home, D; Sinha, U
2021, arXiv:2105.11881

Papers in Press – In Conference Proceedings

1. RaFiDe Part 2 : Signal anomaly detection and prediction of astronomical data for a radio astronomy observation planner
Bhat, Shashank Sanjay*; Prabu, T; Saha, Snehanshu
URSI GASS 2021, Rome, Italy, 28 August – 4 September 2021

2. ArXiv in the open access era: Its usage and impact on physics researches
Nagaraj, M N; Bhandi, M K
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conferences attended & institutions visited

Name	Conferences attended / Institutions visited	Title of paper/talk
Abhishek Ghadai	Complex Fluids 2020 Meeting Indian Institute of Technology Bombay Mumbai 10 – 12 December 2020	
Abhishek Mathur	Conference on Quantum Spacetime and the Renormalization Group University of Southern Denmark, Odense 12 – 16 October 2020	Entropy and the link action in the causal set path-sum
	The Virtual Causet Meeting Raman Research Institute 17 December 2020	Entropy and the link action in the causal set path-sum
Aditi Agarwal	39th Astronomical Society of India Meeting ICTS-TIFR Bengaluru, IISER Mohali, IIT Indore and IUCAA, Pune 18 – 23 February 2021	Multi-band behavior of the TeV blazar PG 1553+113 I optical range on diverse timescales
Adwaith KV	Conference on Lasers and Electro-Optics 11 – 15 May 2020	
Agnibha De Sarkar	Conference on Gamma Ray Halos Around Pulsar 1 – 3 December 2020	
	Astronomy Winter School: High Energy Astrophysics National Centre for Theoretical Sciences Taiwan 18 – 22 January 2021	
Akash Kumar Patwa	SKA India CD/EoR& Cosmology Group 8 March 2021	Drift scan strategy for detecting the 21cm EoR power system

Name	Conferences attended / Institutions visited	Title of paper/talk
Alakananda Patra	National Workshop on Advanced Analytical Techniques for Quality Control of Pharmaceuticals National Institute of Pharmaceutical Education and Research, Hyderabad 3 – 4 July 2020	
	Workshop on XRD Theory, Applications and Data Analysis Malvern Panalytical & Kumaraguru College of Engineering 6 – 7 August 2020	
Andal Narayanan	Tata Institute of Fundamental Research, Hyderabad 29 September 2020	The versatile electromagnetically induced transparency effect: Fundamentals and applications (*Invited*)
	Students Conference on Quantum Physics and TechnologyNational Institute of Science Education and Research, Bhubaneshwar 21 February 2021	The versatile electromagnetically induced transparency effect: Fundamentals and applications. (*Invited*)
Anirban Dutta	8thAtomDB Workshop and Advanced Spectroscopy School Harvard Smithsonian Center for Astrophysics USA 3 – 5 August 2020	
Ashwin Devaraj	39th Astronomical Society of India Meeting ICTS-TIFR Bengaluru, IISER Mohali, IIT Indore and IUCAA Pune 18 – 23 February 2021	NuSTAR view of the cyclotron line source, XTE J1946+274
Biman Nath	Inter University Centre for Astronomy and Astrophysics, Pune 13 August 2020	Neon signs in galactic cosmic rays: Massive young star clusters as important acceleration sites (*Invited*)
Biswajit Paul	California Institute of Technology, USA 5 October 2020	Indian X-ray Polarimeter
	Inter University Centre for Astronomy and Astrophysics, Pune 22 October 2020	Neutron stars in X-ray binaries: Surprises every now and then
	Thapar University, Punjab 22 November 2020	X-ray Astronomical Spectroscopy

Name	Conferences attended / Institutions visited	Title of paper/talk
	Program on 5 Years of Astrosat Indian Space Research Organisation, Bengaluru 21 January 2021	Study of some accretion powered X-ray pulsars with LAXPC
	Conference of High-Energy Astrophysics Japan 9 March 2021	AstroSat, POLIX and some future X-ray instrumentation activities
Chandeshwar Misra	Soft Matter: Young Investigators e- Meet 3 – 5 December 2020	The role of solvent microstructure on the aging dynamics and rheology of aqueous suspensions of a soft colloidal clay
	Complex Fluids 2020 Meeting Indian Institute of Technology Bombay Mumbai 10 – 12 December 2020	The role of solvent microstructure on the aging dynamics and rheology of aqueous suspensions of a soft colloidal clay
Deepak Mehta	Conference on Thirsting for Theoretical Biology International Centre for Theoretical Sciences-Tata Institute of Fundamental research 11 – 22 January 2021	
Girish BS	Webinar on ADC/DAC &RFSoc Architecture Avnet India 28 April 2020	
	Webinar on RFDC IP block and Vivado Design Flow, Avnet India 7 May 2020	
	Colloquium Series on Recent Advances in Astronomy and Space Sciences Indian Institute of Technology, Indore 9 September 2020	
	39th Astronomical Society of India Meeting ICTS-TIFR Bengaluru, IISER Mohali, IIT Indore and IUCAA, Pune 17 – 23 February 2021	
	Webinar on Xilinx India Aerospace & Defense Summit 17 – 24 February 2021	

Name	Conferences attended / Institutions visited	Title of paper/talk
Gunjan Tomar	XIX International Workshop on Neutrino Telescopes 18 – 26 February 2021	
	39th Astronomical Society of India Meeting ICTS-TIFR Bengaluru, IISER Mohali, IIT Indore and IUCAA, Pune 18 – 23 February 2021	
Ion Santra	Bangalore School on Statistical Physics XI 29 June – 10 July 2020	
Kamini PA	39th Astronomical Society of India Meeting ICTS-TIFR Bengaluru, IISER Mohali, IIT Indore and IUCAA, Pune 18 – 23 February 2021	
Madhavan Varadarajan	Ashoka University 11 November 2020	Quantum gravity: A view from general relativity (*Invited*)
Madhavi S	39th Astronomical Society of India Meeting ICTS-TIFR Bengaluru, IISER Mohali, IIT Indore and IUCAA, Pune 17, 18 February 2021	
Manami Roy	39th Astronomical Society of India Meeting ICTS-TIFR Bengaluru, IISER Mohali, IIT Indore and IUCAA, Pune 18 – 23 February 2021	Gamma-Ray and radio background constraints on cosmic rays in milky way circumgalactic medium
	Conference on Fundamentals of Gaseous Halos (HALO21) Kavli Institute for Theoretical Physics 11 January – 5 March 2021	1. Gamma-Ray and radio background constraints on cosmic rays in milky way circumgalactic medium 2. A panoramic view of the circumgalactic medium in the photoionized precipitation model
	Centre for Theoretical Physics Polish Academy of Science, Warsaw 15 March 2021	Unfolding the mystery of the galactic halo
Manjunath Kaddipujar	6th Webinar on Impact of Covid-19 on Academics and Societal Life: Role of Social Media Indian Library Association and Kalyan Karnataka Librarians 20 May 2020	

Name	Conferences attended / Institutions visited	Title of paper/talk
	7th Webinar on Access and Impact of Information and Research in Digital Content Indian Library Association and Association of Indian Law Libraries 23 May 2020	
	Webinar on The Place of Library in National Education Policy 2020: Integration of Learning Landscapes Karnataka State Library Association 12 August 2020	
	UESCO-NDLI Regional Webinar: Access to Information during the Covid-19 Crisis 28 September 2020	
	Webinar on Online Education: Transition of Libraries and Library Services Balani Infotech Pvt. Ltd. 30 September 2020	
	Seminar on Redesigning of Library Services In the Covid-19 Environment Karnataka University, Dharwad 28 October 2020	
	Symposium on Open Access to Archives to Support Humanities Research in India Azim Premji University, Bengaluru 3 February 2021	
	Seminar on Planning and Implementation of Library and Information Services in the Changing Digital Environment Karnataka University, Dharwad 22 March 2021	
Marichandran V	British Liquid Crystal Society Annual Training Workshop 7 – 8 January 2021	
MayuriS Rao	Science at Low Frequencies Conference 1 – 4 December 2020	
	Summer All Zoom Epoch of Reionisaton Astronomy Conference 29 January 2021	Combating systematics: Ground-based global EoR experiments

Name	Conferences attended / Institutions visited	Title of paper/talk
Nagaraj MN	LIS Academy Distinguished Lecture on Role of Libraries in Implementation of NEP-2020 Framework 12 December 2020	
	Webinar on Restoring Pride of Place to Libraries and Librarians – A Demand Side Perspective LIS Academy 9 January 2021	
Nancy Verma	Conference on Lasers and Electro-Optics 11 – 15 May 2020	
	OSA Ultrafast Optical Phenomena Technical Group Workshop 25 – 29 May 2020	Femtosecond laser-induced periodic surface structure on fused silica surface
Nayantara Gupta	Conference on Gamma Ray Halos Around Pulsar 1 – 3 December 2020	
	39th Astronomical Society of India Meeting ICTS-TIFR Bengaluru, IISER Mohali, IIT Indore and IUCAA Pune1 8 – 23 February 2021	Transient astrophysical phenomena (*Invited*)
Nomaan X	The Virtual Causet Meeting Raman Research Institute 26 – 28 August 2020	Entanglement entropy: Examples and questions
	Conference on Quantum Spacetime and the Renormalization Group University of Southern Denmark, Odense 12 – 16 October 2020	Entanglement entropy of causal set de Sitter horizons
Palak	Soft Matter: Young Investigators e- Meet 3 – 5 December 2020	Side branched patterns, coalescence and stable interfaces during radial displacement of a viscoelastic fluid
	Complex Fluids 2020 Meeting Indian Institute of Technology Bombay, Mumbai 10 – 12 December 2020	Side branched patterns, coalescence and stable interfaces during radial displacement of a viscoelastic fluid

Name	Conferences attended / Institutions visited	Title of paper/talk
Prabu T	Indian Pulsar Timing Array Student Week 9 – 12 April 2020	
	Indian Pulsar Timing Array Science Week 13 – 22 April 2020	
	FRB 2020 Thailand Meeting 6 – 9 July 2020	
	International Pulsar Timing Array Catch-up Meeting 22 – 23 September 2020	
	Conference on Future Trends in Radio Astronomy Instrumentation RadioNet Max Planck Institute for Radio Astronomy 21 – 22 September 2020	
	Engineering for Research Symposium 10 – 11 October 2020	
	39th Astronomical Society of India Meeting ICTS-TIFR Bengaluru, IISER Mohali, IIT Indore and IUCAA, Pune 18 – 23 February 2021	
Pradip Kumar Bera	Complex Fluids 2020 Meeting Indian Institute of Technology Bombay, Mumbai 10 – 12 December 2020	Earthquake-like properties of the flow of soft materials below yield stress
Pramod Pullarkat	Indian Academy of Neuroscience Meeting 4 – 7 October 2020	Cytoskeletal contributions to axonal stretch response (*Invited*)
	Bangalore Developmental Biology Club Meeting 30 October 2020	Mechanical and shape responses of axons (*Invited*)
	Complex Fluids 2020 Meeting Indian Institute of Technology Bombay, Mumbai 10 – 12 December 2020	Strain-softening response of axons
	65th Meeting of the Biophysical Society, USA 25 February 2021	An actin-spectrin periodic skeleton acts as an axonal shock absorber (*Invited*)

Name	Conferences attended / Institutions visited	Title of paper/talk
Raghunathan A	The Applied Computational Electromagnetics Society Conference 2020, USA 22 – 26 March 2020	Wide band antenna with ultra-smooth characteristics (*Invited*)
Rajkumar Biswas	Soft Matter: Young Investigators e- Meet 3 – 5 December 2020	Quantifying the destructuring of a thixotropic colloidal suspension using falling ball viscometry
	Complex Fluids 2020 Meeting Indian Institute of Technology Bombay, Mumbai 10 – 12 December 2020	Quantifying the destructuring of a thixotropic colloidal suspension using falling ball viscometry
Ramesh B	39th Astronomical Society of India Meeting ICTS-TIFR Bengaluru, IISER Mohali, IIT Indore and IUCAA, Pune 18 – 23 February 2021	Observing in mm-waves with single dishes (*Invited*)
Ranita Jana	Michigan Cosmology Summer School, USA 1 – 5 June 2020	
	Fundamentals of Gaseous Halos, UC Santa Barbara 11 January – 5 March 2021	
Ranjini Bandyopadhyay	E-Conference on Soft Matter 2020 15 – 17 July 2020	Side branched patterns and proportionate growth in the displacement of a viscoelastic fluid by a Newtonian liquid
Reji Philip	Bishop Moore College, Mavelikkara 14 May 2020	Nonlinear optics of nanomaterials
	S.D. College, Alleppey 28 November 2020	Nonlinear optics: Fundamentals and applications
	UGC Refresher Course Bharatidasan University, Tiruchirapalli 5 December 2020	Nonlinear optics in the nanodomain (*Invited*)
	St. Joseph's College, Alleppey 19 January 2021	Fundamentals of nonlinear optics
	Providence College, Calicut 24 February 2021	The Raman effect
	UGC Refresher Course Bangalore University, Bengaluru 18 March 2021	Nonliear optics in nanodomain (*Invited*)

Name	Conferences attended / Institutions visited	Title of paper/talk
Ritu Nehra	Maglab Virtual 2021 Theory Winter School on Modern Aspects of Quantum Condensed Matter 11 – 15 January 2021	
	Program Non-Hermitian Physics International Centre for Theoretical Sciences Bengaluru 21 – 26 March 2021	
Sachidananda Barik	Complex Fluids 2020 Meeting Indian Institute of Technology Bombay Mumbai 10 – 12 December 2020	Transient stress relaxation in dense particulate suspensions in a shear induced jammed state
Sanhita Kabiraj	43rd COSPAR Scientific Assembly, Australia 29 January 2021	1. Broad brand X-ray characteristics of the transient pulsar GRO J2058+42 2. A glimpse of COSPAR capacity building workshop
Sanjib Sabhapandit	Lakhimpur Girl's College, Assam 17 July 2020	Large deviations in non-equilibrium systems
	Arya Vidyapeeth College, Assam 27 July 2020	Large deviations in non-equilibrium systems
	International Centre for Theoretical Sciences Bengaluru 4 March 2021	Active Brownian motion with directional reversals
Saptarishi Chaudhuri	Webinar on Physical Chemistry Karnataka Science and Technology Academy Bengaluru 26 November 2020	Quantum technologies (*Invited*)
	Student Conference on Photonics and Quantum Technology 2021 National Institute of Science Education and Research, Bhubaneswar 25 February 2021	Emerging quantum technologies with coherently driven hot and cold atoms (*Invited*)
Saurabh Kaushik	Conference on Mechano-Genomics Seminar Series TH Zurich & Paul Scherrer InstituteSwitzerland (Ongoing)	

Name	Conferences attended / Institutions visited	Title of paper/talk
Saurabh Singh	Packed Ultra-wideband Mapping Array Workshop 2020 18 – 20 August 2020	Overview on HERA simulations
	3rd Global 21-cm Workshop University of Cambridge 19 – 22 October 2020	Updates on SARAS 3 and PRATUSH (*Invited*)
	Science at Low Frequencies VII Conference University of Amsterdam, The Netherlands 1 – 4 December 2020	SARAS 3: A precision radiometer for observations of cosmic dawn
Sayantan Majumdar	Complex Fluids 2020 Meeting Indian Institute of Technology Bombay Mumbai 10 – 12 December 2020	Yielding and energy dissipation in dense suspensions of cohesive athermal particles (*Invited*)
	International Conference on Soft Materials Malaviya National Institute of Technology Jaipur 13 – 18 December 2020	Signature of jamming under steady shear in dense particulate suspensions
Sebanti Chattopadhyay	Complex Fluids 2020 Meeting Indian Institute of Technology Bombay Mumbai 10 – 12 December 2020	Role of inter-particle attractive interactions on shear banding and dissipation in dense suspensions
Sourav Bhadra	39th Astronomical Society of India Meeting ICTS-TIFR Bengaluru, IISER Mohali, IIT Indore and IUCAA, Pune 18 – 23 February 2021	
Srinivasa HT	Faculty Development Programme on Recent Trends in Advanced Chemistry University of Petroleum and Energy Studies Uttarakhand 8 – 13 June 2020	
	International Conference on Advanced Material Science and Applications MS Ramaiah Institute of Technology, Bengaluru 3 – 4 September 2020	Rotational diffusion of aromatic diketone derivatives in polar and nonpolar solvents

Name	Conferences attended / Institutions visited	Title of paper/talk
Srivani KS	Webinar on ADC/DAC &RFSoc Architecture Avnet India 28 April 2020	
	Webinar on RFDC IP block and Vivado Design Flow Avnet India 7 May 2020	
	Colloquium Series on Recent Advances in Astronomy and Space Sciences Indian Institute of Technology, Indore 9 September 2020	
	Meeting on Radio Noise Measurement in India Ministry of Communications 4 February 2021	
	39th Astronomical Society of India Meeting ICTS-TIFR Bengaluru, IISER Mohali, IIT Indore and IUCAA Pune 17 – 23 February 2021	
	Webinar on Xilinx India Aerospace & Defense Summit 17 – 24 February 2021	
Sumati Surya	Rad-boud University, The Netherlands 5 June 2020	Quantum dynamics for Causal Sets: Three approaches
	Conference on Quantum Gravity 2020 Perimeter Institute, Canada 13 – 17 July 2020	The quantum dynamics of causal sets: Directions and challenges (*Invited*)
	The Virtual Causet Meeting Raman Research Institute 26 – 28 August 2020	
	Conference on Quantum Spacetime and the Renormalization Group University of Southern Denmark Odense 12 – 16 October 2020	Evolutionary RG in causal set theory (*Invited*)
	Legacy School, Bengaluru 7 January 2021	Pursuing a life/career in science

Name	Conferences attended / Institutions visited	Title of paper/talk
	Conference on Women at the Intersection of Mathematics and Theoretical Physics Perimeter Institute, Canada 22 – 25 February 2021	Mathematical puzzles from causal set quantum gravity (*Invited*)
Supurna Sinha	Conference on Current Trends in Quantum Information Processing Indian Institute of Science, Bengaluru 24 July 2020	
	Conference on Statistical Biological Physics: From Single Molecule to Cell International Centre for Theoretical Sciences Bengaluru 7 - 18 December 2020	
Swarnadeep Bakshi	Complex Fluids 2020 Meeting Indian Institute of Technology Bombay Mumbai 9 December 2020	
Tamal Sarkar	Complex Fluids 2020 Meeting Indian Institute of Technology Bombay Mumbai 10 – 12 December 2020	1. Gelation kinetics of carbon dots embedded silica gel 2. Effective chitosan-silica-TIO2 hybrid nanocomposite gels for adsorption of dye
Urbasi Sinha	Symposium on Quantum Information and Computation Institute of Electrical and Electronics Engineers, Hyderabad 2 July 2020	Quantum experiments using satellite technology (*Invited*)
	World Summit on the Information Society Forum 2020 Session on Cybersecurity in the era of Quantum Information Technology: Challenges and Considerations for ICT Networks 31 July 2020	Security threat to networks: Solution may be quantum (*Invited*)
	Virtual Roadshow on Showcasing Cyber Security R&D 6 November 2020	
	Conference of India Internet Foundation 1 December 2020	Quantum communications at RRI Bangalore (*Invited*)

Name	Conferences attended / Institutions visited	Title of paper/talk
	International Conference on Quantum Fundamentals, Technology and Applications 5 December 2020	Quantum state interferography (*Invited*)
	15h Edition of NASSCOM-DSCI Annual Information Security Summit 17 December 2020	Quantum communications (*Invited*)
	The Young Scientists' Conference India International Science Festival 22 December 2020	Exotic world in the foundations of quantum mechanics (*Invited Review)*
	Webinar on Quantum Technologies Indian Institute of Space Science and Technology Alumni Association 16 January 2021	Quantum communications (*Invited*)
	ATAL Faculty Development Workshop on Quantum Computing Thakur College of Engineering and Technology 22 January 2021	Quantum communications (*Invited*)
	Quantum Information and Computing Workshop The Indian Institute of Information Technology Design and Manufacturing, Kurnool 25 January 2021	Photonic quantum science and technologies
	Student Conference on Advances in Optics Tata Institute of Fundamental Research Mumbai 5 February 2021	Secure quantum communications at RRI Bangalore (*Invited*)
	Royal Society Yusuf Hamied Workshop for India and the UKRoyal Society, UK and Indian National Science Academy 4 March 2021	Photonic quantum science and technologies (*Invited*)
	Workshop on International Womens' Day 2021 Vigyan Prasar and Office of Principal Scientific Adviser, Government of India 8 March 2021	

Name	Conferences attended / Institutions visited	Title of paper/talk
Urna Basu	Bangalore School on Statistical Physics XI 29 June – 10 July 2020	Nonequilibrium response theory
	Physics Colloquium Indian Institute of Science, Bengaluru 27 November 2020	Active Brownian motion in 2D
	University of Edinburgh, UK 13 January 2021	Active Brownian motion in two-dimensions under stochastic resetting
Vani Hiremath	Library Technology Conclave 27 – 30 January 2021	
Vaibhav Raj Singh Parmar	Complex Fluids 2020 Meeting Indian Institute of Technology Bombay Mumbai 10 – 12 December 2020	Effect of aging on cracking of desiccating Laponite suspensions
	International Conference on Soft Materials Malaviya National Institute of Technology Jaipur1 3 – 18 December 2020	Effect of aging on cracking of desiccating Laponite suspensions
Vinutha C	39th Astronomical Society of India Meeting ICTS-TIFR Bengaluru, IISER Mohali, IIT Indore and IUCAA, Pune 18 – 23 February 2021	
Yogesh Arya	Complex Fluids 2020 Meeting Indian Institute of Technology Bombay, Mumbai 10 – 12 December 2020	Behaviour of Laponite nanoplatelets with tunable interactions

colloquia & seminars

Name	Title	Date
Gautam Menon Ashoka University, Sonepat and Institute of Mathematical Sciences, Chennai	COVID-19: What the future might hold	22 May 2020
GV Pavan Kumar Indian Institute of Science Education and Research, Pune	Optothermal assembly of colloids	5 June 2020
Jyoti R SethIndian Institute of Technology Mumbai	Breaking wax networks in crude oil using high electric fields	19 June 2020
Sandeep Kirshna National Centre for Biological Sciences, Bengaluru	The chemical basis of metabolic interdependence	4 July 2020
Guruswamy Kumaraswamy Indian Institute of Technology Mumbai	3D printing of waste-derived high density polyethylene	17 July 2020
Rama Govindarajan International Centre for Theoretical Sciences, Bengaluru	Chaotic dynamics of ellipsoids in fluid	31 July 2020
Sonali Sachdeva Peking University, Beijing	Interplay of structure, stellar activity and environment of galaxies	7 August 2020
Jayaraman N Chengalur National Centre for Radio Astronomy, Pune	Evolution of the atomic gas content of galaxies	11 August 2020
Nitin Kumar Indian Institute of Technology Mumbai	Controlling elasticity and complex dynamics of biopolymer-based active liquid crystals	14 August 2020
Ritaban Chatterjee Presidency University, Kolkata	Blazars in AstroSat era	18 August 2020

Name	Title	Date
Dipankar Bhattacharya Inter-University Centre for Astronomy and Astrophysics, Pune	Polarised high energy emission from astrophysical sources	25 August 2020
Prateek Sharma Indian Institute of Science Bengaluru	Circumgalactic medium as seen through idealized models	1 September 2020
Madivala G Basavaraj Indian Institute of Technology Madras	Evaporation driven self-assembly of colloids	11 September 2020
Satyajit Rath Indian Institute of Science Education and Research, Pune	COVID-19: Immunity in the crosshairs	24 September 2020
Chandan Dasgupta Indian Institute of Science and International Centre for Theoretical Sciences, Bengaluru	Active matter at high densities	25 September 2020
Basudeb Maji Broad Institute of MIT and HARWARD, Cambridge	CRISPR: A Crispy Gift from Microorganism to Mankind for Gene-editing	29 October 2020
Sayan Kar Indian Institute of Technology Kharagpur	The ubiquitous Raychaudhuri equation and its consequences	5 November 2020
Seshadri Sridhar Raman Research Institute Bengaluru	Supermassive black holes in galactic nuclei: A perspective on the 2020 Physics Nobel Prize	12 November 2020
SK Minhajur Rahman National Centre for Radio Astrophysics, Pune	Exploring pulsar radio emission via the hydrodynamic branch of Langmuir wave instability	24 November 2020
Susmita Das Delhi University, New Delhi	Out-of-plane self-propulsion of droplets on heated lubricant-impregnated surfaces	18 December 2020
Arpita Das Saha Institute of Nuclear Physics Kolkata	Laser induced coherent phenomena in the Rubidium atomic medium	21 January 2021
Pritha Dolai International Centre for Theoretical Sciences, Bengaluru	Active particles in a single-file: effect of confinement	25 January 2021

Name	Title	Date
Aditya Rotti University of Manchester, UK	Novel approaches to deriving cosmological constraints via measurements of the Sunyaev-Zeldovich effect	27 January 2021
Seema Satin Indian Institute of Science Education & Research, Pune	Stochastic fluctuations in strong gravity regions and compact stars: An approach towards studying statistical properties of dense matter in astrophysical objects and their dynamical properties	27 January 2021
Rijutha Jaganathan Aarhus University, Denmark	The contribution of PAHx to interstellar chemistry – a Laboratory Study	29 January 2021
Sushanta Kumar Pal Indian Institute of Technology Delhi, New Delhi	Spin-orbit beams: An overview	12 February 2021
Kumar Shivam National Institute of Technology Patna	Training a computer program to recognize handwriting using Bayes Theorem	17 February 2021
Chao-Yang Lu University of Science and Technology of China, China	Quantum supremacy and beyond	18 February 2021
Gregor Weihs University of Innsbruck, Austria	Extraordinary claims require extraordinary evidence: Closing loopholes in Bell's inequality experiments	25 February 2021
Chiranjeeb Singha Chennai Mathematical Institute Chennai	Studies in thermal aspects of Schwarzchild spacetime	26 February 2021
David Pine New York University, USA	Self-assembly of colloidal diamond for photonics	11 March 2021
Rahul Sharma Indian Institute of Science Education and Research, Mohali	Broad-band look at the transient Neutron Star X-ray binaries: MXB 1658-298 and SAX J1748.9-2021	18 March 2021

Online Workshop on Recent Trends and Developments in Secure Quantum Communications as well as Quantum Sensing and Metrology

17 – 18 August 2020

Name	Title	Date
Ravindra Pratap Singh Physical Research Laboratory, Ahmedabad	Quantum Key Distribution: Using multi-photon pulses to the advantage	17 August 2020
Saikat Ghosh Indian Institute of Technology, Kanpur	Atomic coherence and photon memories	17 August 2020
Piet Schmidt Physikalisch-Technische Bundesanstalt Germany	Optical Clocks with Highly Charged Ions for Tests of Fundamental Physics	17 August 2020
Thomas Jennewein University of Waterloo, Canada	Novel avenues for robust free-space quantum communications	17 August 2020
Urbasi Sinha Raman Research Institute, Bengaluru	Quantum experiments with satellite technology	17 August 2020
Alexander Ling National University of Singapore, Singapore	SpooQy Action at a Distance - Measuring entanglement generation onboard a nano-satellite	18 August 2020
Umakant Rapol Indian Institute of Science Education and Research, Pune	Atom interferometry at IISER Pune	18 August 2020
Subhadeep De Inter University Centre for Astronomy & Astrophysics, Pune	Optical atomic clock and quantum metrology	18 August 2020
Sayan Patra LaserLaB and Department of Physics and Vrije Universiteit Amsterdam, The Netherlands	Fundamental physics from molecular vibrations: Towards a molecular-ion optical clock	18 August 2020

visitors

Name and Institution	Duration of Stay
SK Minhajur Rahman National Centre for Radio Astrophysics Pune	24 November 2020
Rijutha Jaganathan Aarhus University Denmark	29 January 2021
Smijesh N Mahatma Gandhi University Kerala	27 February – 6 March 2021
Urna Basu SN Bose National Centre for Basic Sciences Kolkata	13 – 26 March 2021
Kishan Sankharva Indian Institute of Technology Kanpur	15 – 31 March 2021

visiting students' programme

Mentor	Student
Shiv Sethi	Siddhant
Mayuri S Rao	Pratik Dongre
A Raghunathan	K Kavitha
Gautam V Soni	Jyoti Sharma
Andal Narayanan	JK Saswath
B Ramesh	R Aishwarya
Reji Philip	Gopika Anil
	MS Amogh
Pramod Pullarkat	Kshitija Joshi
Hema Ramachandran	Gayatri Reshma Sasidharan
	BS Karthik
	M Bindushree
Sayantan Majumdar	Vibha Balaji
	Shibil Adam Kunikkadan
Dibyendu Roy	Monira Fatma
Vikram Rana	Suhasini S Rao
Ranjini Bandyopadhyay	Nizzy Peter

Raman Research Institute

statement of accounts

S. JANARDHAN & ASSOCIATES
CHARTERED ACCOUNTANTS

VIJAY BHATIA, B.com., F.C.A.,
BALAKRISHNA S.BHAT, B.com., F.C.A.,
B. ANAND, B.Sc.,F.C.A.,

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No.11, Crescent Road
Bangalore - 560 001

Phone :22265438, 22260055
22202709 Fax: 22265572
E-mail : ca.sjassociates@gmail.com

INDEPENDENT AUDITORS REPORT

To
Members of Raman Research Institute

Opinion

We have audited the accompanying financial statements of M/s Raman Research Institute, ("Institute"), Sir C V Raman Avenue, Sadashivanagar, Bangalore 560080, which comprises of the balance sheet as at March 31st 2021, the Income &, Expenditure Account for the year then ended, the Receipts and Payment Account for the year then ended, and notes to the financial statements, including a summary of significant accounting policies

In our opinion and to the best of our information and according to the explanations given to us, except for the effects of the matter described in the Basis for Opinion section of our report, the accompanying financial statements give a true and fair view of the financial position of the Institute as at March 31, 2021, and of its financial performance and its receipts and payments for the year then ended in accordance with the Accounting Standards issued by the Institute of Chartered Accountants of India (1CAI).

Basis for Opinion

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

Responsibilities of Management and those charged with Governance for the Financial Statements.

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

S. Janardhan & Associates Chartered Accountants Bangalore 560 001.

its ability to continue as a going concern, disclosing, as applicable, matters related to going concern and using the going concern basis of management either intends to accounting unless liquidate the Institute or to cease operations, or has no realistic alternative but to do so. Those charged with governance are responsible for overseeing the Institute's financial reporting process.

Auditor's Responsibilities for the Audit of the Financial Statements

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

As part of an audit in accordance with SAs, we exercise professional judgment and maintain professional scepticism throughout the audit. We also:

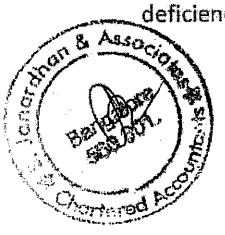
- Identify and assess the risks of material misstatement of the financial statements, whether due to fraud or error, design and perform audit procedures responsive to those risks, and obtain audit evidence that is sufficient and appropriate to provide a basis for our opinion. The risk of not detecting a material misstatement resulting from fraud is higher than for one resulting from error, as fraud may involve collusion, forgery, intentional omissions, misrepresentations, or the override of internal control.

- Obtain an understanding of internal control relevant to the audit in order to design audit procedures that are appropriate in the circumstances, but not for the purpose of expressing an opinion on the effectiveness of the Institute's internal control.

- Evaluate the appropriateness of accounting policies used and the reasonableness of accounting estimates and related disclosures made by management.

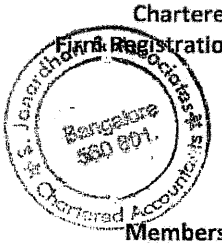
- Conclude on the appropriateness of management's use of the going concern basis of accounting and, based on the audit evidence obtained, whether a material uncertainty exists related to events or conditions that may cast significant doubt on the Institute's ability to continue as a going concern. If we conclude that a material uncertainty exists, we are required to draw attention in our auditor's report to the related disclosures in the financial statements or, if such disclosures are inadequate, to modify our opinion. Our conclusions are based on the audit evidence obtained up to the date of our auditor's report. However, future events or conditions may cause the Institute to cease to continue as a going concern.

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



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

For S Janardhan & Associates
Chartered Accountants
Firm Registration No. 005310S



B Anand
Partner
Membership no 029146
UDIN : 21029146AAAAHT7299

Place : Bangalore
Date : 5th July 2021

RAMAN RESEARCH INSTITUTE, BENGALURU
BALANCE SHEET AS AT 31ST MARCH 2021
UDIN - 21029146AAAAHT7299

(Amount in INR)

CORPUS/CAPITAL FUND AND LIABILITIES	Schedule	Current Year	Previous Year
Corpus/Capital Fund	1	104,98,46,818	103,71,86,702
Reserves & Surplus	2	-	-
Earmarked & Endowment Funds	3	67,67,74,846	63,54,52,816
Secured Loans & Borrowings	4	-	-
Unsecured Loans & Borrowings	5	-	-
Deferred Credit Liabilities	6	-	-
Current Liabilities & Provisions	7	2,03,99,221	1,91,29,454
TOTAL		**174,70,20,885**	**169,17,68,972**
ASSETS			
Fixed Assets	8	84,94,75,308	90,04,21,237
Investments- from earmarked & endowment funds	9	70,58,45,983	59,32,17,739
Investments-Others	10	1,00,00,000	1,00,00,000
Current Assets, Loans & Advances	11	18,16,99,594	18,81,29,996
TOTAL		**174,70,20,885**	**169,17,68,972**
Significant Accounting Policies	24		
Contingent Liabilities and Notes on Accounts	25		

As per our report of even date
for M/s **S. JANARDHAN & ASSOCIATES**
Chartered Accountants
FRN 005310S

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

(Sridhar S)
Director

(B. Anand)
Partner
M No. 029146

BENGALURU / 05-07-21

RAMAN RESEARCH INSTITUTE, BENGALURU

INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR ENDED 31ST MARCH 2021

UDIN - 21029146AAAAHT7299

(Amount in INR)

INCOME	Schedule	Current Year	Previous Year
Income from Sales/Services	12	-	-
Grants/Subsidies	13	61,31,39,234	53,61,59,736
Fee/Subscriptions	14	-	-
Income from Investments for earmarked/endowment funds)	15	-	-
Income from Royalty	16	-	-
Interest Earned	17	58,82,798	75,46,893
Other Income	18	1,51,45,694	76,75,314
Increase/Decrease in stock of finished goods	19	-	-
TOTAL (A)		**63,41,67,726**	**55,13,81,943**
EXPENDITURE			
Establishment Expenses	20	43,56,52,202	34,72,24,885
Other Administrative Expenses	21	11,33,48,305	13,65,76,398
Expendtiture on Grants/Subsidies	22	-	-
Interest	23	-	-
Depreciation (Net as per Schedule 8)		6,96,39,234	6,73,63,736
TOTAL (B)		**61,86,39,741**	**55,11,65,019**
INTEREST ON GRANT BALANCES TRF TO BHARATKOSH - Sch 7(A)(1b)		**25,28,635**	**17,85,815**
BALANCE-SURPLUS/(DEFICIT) CARRIED TO CORPUS/CAPITAL FUND - Sch. 1(2b)		**1,29,99,350**	**(15,68,891)**
Significant Accounting Policies	24		
Contingent Liabilities and Notes on Accounts	25		

As per our report of even date

for M/s **S. JANARDHAN & ASSOCIATES**

Chartered Accountants

FRN 005310S

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

(Sridhar S)
Director

(B. Anand)
Partner
M No. 029146

BENGALURU / 05-07-21

RAMAN RESEARCH INSTITUTE, BENGALURU
RECEIPTS AND PAYMENTS STATEMENT FOR THE YEAR ENDED 31ST MARCH 2021
UDIN - 21029146AAAAHT7299

(Amount in INR)

RECEIPTS	Current Year	Previous Year	PAYMENTS	Current Year	Previous Year
I. Opening Balances			**I. Expenses**		
a) Cash in hand	300	281	a) Establishment Exp	43,56,52,202	34,72,24,885
b) Bank Balances	4,15,52,578	1,81,70,199	b) Admin Expenses	11,33,48,318	13,65,77,037
c) Deposits	23,98,76,801	33,06,96,492	c) PF-Final Settlement	2,03,06,638	3,11,61,685
d) Stamps (Franking M/C)	8,620	14,407	d) Pension Payout	-	-
II. Grants Received			**II. Payments made against projects**	5,48,75,764	6,09,77,259
a) From Govt. of India	61,28,00,000	51,88,24,000			
b) From State Govt.	-	-	**III. Investment and deposits made**		
c) From other sources	10,53,67,898	6,92,03,040	a) Out of earmarked funds	-	-
			b) Out of own funds (investment-others)	-	-
III. Income on Investments from					
a) Earmarked & Endowment Funds	-	-	**IV. Expenditure on Fixed Assets & CWIP**	4,22,67,303	5,51,50,309
b) Own Funds	-	-			
			V. Refund of surplus money / loans		
IV. Interest Received			a) To Govt. of India	-	-
a) On Bank deposits	1,29,25,379	2,28,58,106	b) To State Govt	-	-
b) on Loans, Advances etc.	83,754	1,26,229	c) To other fund providers	-	-
V. Other Income (Specify)	1,52,19,526	77,24,073	**VI. Finance charge (Interest)**	-	-
VI. Amount Borrowed	-	1,53,975	**VII. Other Payments (Specify)**	-	-
VII. Any other Receipts (Specify)			a) TDS Receivable	6,67,719	14,49,366
a) Advances	49,80,186	3,88,42,932	b) Advances	1,87,16,278	4,79,84,183
b) Receivables	1,47,86,982	1,08,84,624	c) Investments (Nett)	8,44,347	28,10,770
c) Accrued Interest	5,99,623	1,72,485	d) EMD, SD, CD (Deposits)	-	19,92,679
d) Investments (Nett)	4,30,05,923	1,13,09,400	e) Bills Payable	2,17,12,502	1,75,94,585
e) Overheads	-	29,70,661	f) Payroll Recoveries	4,56,78,849	5,35,62,615

RAMAN RESEARCH INSTITUTE, BENGALURU
RECEIPTS AND PAYMENTS STATEMENT FOR THE YEAR ENDED 31ST MARCH 2021
UDIN - 21029146AAAAHT7299

(Amount in INR)

RECEIPTS	Current Year	Previous Year	PAYMENTS	Current Year	Previous Year
f) EMD, SD, CD (Deposits)	4,35,000	7,40,000	g) Deposits (for services)	-	-
g) Pension Corpus	7,23,718	2,95,00,000	h) Duties & Taxes	10,92,808	15,55,883
h) Employees's subscription	2,62,18,626	1,88,55,710	i) Provision	79,019	11,66,059
			j) PF-Withdrawals	1,33,15,136	1,09,01,000
			h) CPF (Emplyr Share)-Trf to Pension	-	2,95,00,000
			VIII. Closing Balances		
			a) Cash Balance	17	300
			b) Bank Balances		
			i) Deposit Accounts	32,66,38,753	23,98,76,801
			II) Current/Savings Account	2,33,89,167	4,15,52,578
			c) Postal franking machine	94	8,620
TOTAL	**111,85,84,914**	**108,10,46,614**		**111,85,84,914**	**108,10,46,614**

As per our report of even date
for M/s **S. JANARDHAN & ASSOCIATES**
Chartered Accountants
FRN 005310S

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

(Sridhar S)
Director

(B. Anand)
Partner
M No. 029146

BENGALURU / 05-07-21

RAMAN RESEARCH INSTITUTE, BENGALURU

SCHEDULES FORMING PART OF BALANCE SHEET AS AT 31ST MARCH 2021

(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	103,95,16,741		105,17,30,168	
Addition during the year	11,22,14,948		9,68,79,779	
Less: Deductions during the year *(Includes Capital Work-in-progress)*	6,99,47,645		4,17,29,470	
Less: Depreciation chargeable transferred to Income and Expenditure A/c	6,96,39,234		6,73,63,736	
BALANCE AS AT THE YEAR END		101,21,44,810		103,95,16,741
(2) GRANT BALANCES				
(a) NON-RECURRING GRANT				
Balance as at the beginning of the year		7,49,616		58,71,925
Add: Contributions during the year		6,93,00,000		5,00,28,000
Less: Expenditure incurred during the year		4,22,67,303		5,51,50,309
BALANCE AS AT THE YEAR END		2,77,82,313		7,49,616
(b) RECURRING GRANT				
Balance as at the beginning of the year	(30,79,655)		(15,10,764)	
Transferred from Income & Expenditure-	1,29,99,350		(15,68,891)	
-Account for the year				
BALANCE AS AT THE YEAR END		99,19,695		(30,79,655)
TOTAL (1+2)		**104,98,46,818**		**103,71,86,702**

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

S. Janardhan & Associates Chartered Accountants Bangalore 560 001

RAMAN RESEARCH INSTITUTE, BENGALURU
SCHEDULES FORMING PART OF BALANCE SHEET AS AT 31ST MARCH 2021

Schedule 3- Earmarked/Endowment Funds

(Amount in INR)

Sl No	Funding Agency	Project Name	Opening Balance	Additions during the year	Utilisation			Total Utilisation	Balance as on 31/03/21
					Capital Expenditure	Recurring Expenditure	Advances/ Receivables		
Funded by Government Agencies									
1	DAE	Prof. Krishnakumar-RRF-DAE	1,41,285	-	-	12,00,000	-	12,00,000	(10,58,715)
2	CSIR	SSB Fellowship-Dr. Sadiq	1,80,000	1,80,000	-	3,60,000	-	3,60,000	-
3		SSB Fellowship-Prof Avinash Deshpande	1,50,000	-	-	1,50,000	-	1,50,000	-
4	DBT	Joint Project-Dr. Pramod	(1,85,224)	-	-	2,11,878	-	2,11,878	(3,97,102)
5	DST	DBT-BDTD Grant-Dr. Gautam	30,22,560	-	9,28,530	22,01,290	-	31,29,820	(1,07,260)
6		Ramanujan Fellowship- Dr Pramod	2,06,447	-	-	-	-	-	2,06,447
7		DST-Indo-Russia-P/270-Prof Biman	2,50,000	-	-	2,50,000	-	2,50,000	-
8		DST-Indo-Russia-P/276-Prof Shiv	2,32,600	-	-	2,32,600	-	2,32,600	-
9		DST-QuST grant-Prof Urbasi	21,79,247	98,34,000	-	29,36,119	-	29,36,119	90,77,128
10		DST-Indo-Russia-Prof. Sandeep	14,10,400	-	-	4,15,827	-	4,15,827	9,94,573
11		DST-WOS-A-Dr. Sanjukta	-	18,38,400	-	1,00,000	-	1,00,000	17,38,400
12		DST-Indoltaly-Dr. Urbasi	51,61,547	4,98,964	-	26,28,340	14,35,708	40,64,048	15,96,463
13	IFCPAR	CEFIPRA Grant- Prof Hema R	1,37,525	-	-	1,37,525	-	1,37,525	-
14		CEFIPRA Grant- Dr. Sadiq Rangwala	79,867	-	-	-	-	-	79,867
15	ISRO	PRATUSH-Dr. Mayuri	18,50,324	20,06,000	84,190	24,01,877	-	24,86,067	13,70,257
16		ISRO-Polix Payload-Prof Biswajit	1,21,36,042	-	74,88,952	-	10,25,261	85,14,213	36,21,829
17		ISRO-QKD-Project-Dr. Urbasi	5,18,49,562	2,92,47,534	60,10,861	1,48,88,291	15,29,788	2,24,28,940	5,86,68,156
18	SERB	Ramanujan Fellowship- Dr Sayantan	(7,41,767)	15,00,000	-	2,32,308	-	2,32,308	5,25,925
19		TARE Grant- Dr. Anoop, CUSAT	2,29,632	2,85,000	-	2,82,191	-	2,82,191	2,32,441
20		Ramanujan Fellowship- Dr Urna Basu	88,716	6,72,000	-	67,382	-	67,382	6,93,334
21		Vajra Fellowship-Prof Satya Majumdar	(15,883)	-	-	-	-	-	(15,883)
22		SERB Grant-Dr. Ranjini	3,55,938	5,00,000	-	4,63,556	-	4,63,556	3,92,382
23		Vajra Fellowship-Prof Sanders	(1,81,496)	-	-	-	-	-	(1,81,496)
24	SERB	Ramanujan Fellowship-Dr. Dibyendu	4,61,593	-	-	4,61,593	-	4,61,593	-
25	MeITY	Joint Project-Dr. Urbasi	2,00,00,000	5,76,96,000	-	1,06,13,088	1,46,16,721	2,52,29,809	5,24,66,191
26	INSA	INSA-Fellowshp-Prof. Raghunathan	-	-	-	76,452	-	76,452	(76,452)
27	TIFR	TIFR-Grant-Prof. Krishnakumar	51,398	-	-	3,186	-	3,186	48,212
SUB TOTAL			**9,90,50,313**	**10,42,57,898**	**1,45,12,533**	**4,03,13,503**	**1,86,07,478**	**7,34,33,514**	**12,98,74,697**

Schedule 3- Earmarked/Endowment Funds

(Amount in INR)

Sl No	Funding Agency	Project Name	Opening Balance	Additions during the year	Utilisation			Total Utilisation	Balance as on 31/03/21
					Capital Expenditure	Recurring Expenditure	Advances/ Receivables		
Funded by other than Government Agencies									
1	IKP	GCE Grant-Dr. Gautam Soni	(3,87,915)	11,10,000	-	49,728	-	49,728	6,72,357
SUB TOTAL			**(3,87,915)**	**11,10,000**	**-**	**49,728**	**-**	**49,728**	**6,72,357**
Retirement Funds									
1	-	Gratuity Fund	5,45,78,662	49,07,186	-	1,81,30,696	(1,43,53,459)	37,77,237	5,57,08,611
2		Leave Salary Fund	4,75,10,732	41,84,841	-	1,53,79,955	(1,12,74,817)	41,05,138	4,75,90,435
3		Pension Commutation Fund	21,65,17,145	1,67,74,265	-	1,79,42,478	(1,91,06,123)	(11,63,645)	23,44,55,055
4		RRI Pension Fund	11,05,90,480	56,48,011	-	1,18,21,530	(75,236)	1,17,46,294	10,44,92,197
5		RRI Provident Fund	10,75,93,399	-	-	36,11,905	-	36,11,905	10,39,81,494
SUB TOTAL			**53,67,90,418**	**3,15,14,303**	**-**	**6,68,86,564**	**(4,48,09,635)**	**2,20,76,929**	**54,62,27,792**
GRAND TOTAL			**63,54,52,816**	**13,68,82,201**	**1,45,12,533**	**10,72,49,795**	**(2,62,02,157)**	**9,55,60,171**	**67,67,74,846**

S. Janardhan & Associates Chartered Accountants Bangalore 560 001

RAMAN RESEARCH INSTITUTE, BENGALURU
SCHEDULES FORMING PART OF BALANCE SHEET AS AT 31ST MARCH 2021

(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	14,586		25,26,428	
b) Others **(Includes earnings to be transferred to BHARATKOSH)**	26,95,084	27,09,670	28,19,590	53,46,018
2. Earnest Money Deposit		9,52,000		6,89,500
3. Advances Received		1,00,00,000		1,00,00,000
4. Statutory Liabilities				
a) Overdue	-			
b) Others	-		-	
5. Other Current Liabilities (Incl. Security Deposit)	14,59,928	14,59,928	18,53,136	18,53,136
TOTAL (A)		**1,51,21,598**		**1,78,88,654**
B. PROVISIONS				
1. Gratuity	-		-	
2. Superannuation / Pension	21,353		-	
3. Accumulated Leave Encashment	-		-	
4. Others (Specify)	52,56,270		12,40,800	
TOTAL (B)		**52,77,623**		**12,40,800**
TOTAL (A+B)		**2,03,99,221**		**1,91,29,454**

RAMAN RESEARCH INSTITUTE, BENGALURU
SCHEDULES FORMING PART OF BALANCE SHEET AS AT 31ST MARCH 2021

Schedule 8- Fixed Assets (Amount in INR)

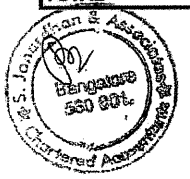
Description		GROSS BLOCK				DEPRECIATION					NET BLOCK
	Rate	Cost /Valuation as at the beginning of theyear	Additions During the year	Deductions during the year	Cost / Valuation at the end of the year	As at the beginning of the year	On additions during the year (Incl. on the OB)	On deductions during the year	Total upto the year end	As at the end of current year	As at the end of Previous Year
A. Fixed Assets											
1. Land											
a) Freehold											
Malleshwaram	-	3,78,735	-	-	3,78,735	-	-	-	-	3,78,735	3,78,735
RMV II Stage	-	31,19,436	-	-	31,19,436	-	-	-	-	31,19,436	31,19,436
HMT Jalahalli	-	8,00,63,261	-	-	8,00,63,261	-	-	-	-	8,00,63,261	8,00,63,261
2. Buildings											
a) On freehold land	1.63	19,37,93,031	27,38,473	-	19,65,31,504	4,20,21,003	31,95,607	-	4,52,16,610	15,13,14,894	15,17,72,028
3. Canteen Infrastructure	4.75	44,09,909	-	-	44,09,909	20,51,244	2,09,471	-	22,60,715	21,49,194	23,58,665
4. Plant Machinery, Equipment	4.75	105,28,35,055	2,92,31,862	-	108,20,66,917	52,35,17,085	5,10,79,454	-	57,45,96,539	50,74,70,378	52,93,17,970
5. Vehicles	9.50	74,51,930	-	-	74,51,930	74,51,929	-	-	74,51,929	1	1
6. Furniture & Fixtures	6.33	1,59,43,141	3,10,919	-	1,62,54,060	1,20,24,602	10,27,203	-	1,30,51,805	32,02,255	39,18,539
8. Computer Peripherals	16.21	17,31,53,722	1,46,65,091	-	18,78,18,813	15,81,89,410	31,21,425	-	16,13,10,835	2,65,07,978	1,49,64,312
9. Library Books	4.75	23,11,89,958	5,53,494	-	23,17,43,452	15,48,45,076	1,10,06,074	-	16,58,51,150	6,58,92,302	7,63,44,882
Total Fixed Assets		176,23,38,178	4,74,99,839	-	180,98,38,017	90,01,00,349	6,96,39,234	-	96,97,39,583	84,00,98,434	86,22,37,829
B. Work in Progress											
Capital Assets		3,81,83,408	2,62,43,018	5,50,49,552	93,76,874	-	-	-	-	93,76,874	3,81,83,408
Total Capital Work in Progress		3,81,83,408	2,62,43,018	5,50,49,552	93,76,874	-	-	-	-	93,76,874	3,81,83,408
Grand Total		180,05,21,586	7,37,42,857	5,50,49,552	181,92,14,891	90,01,00,349	6,96,39,234	-	96,97,39,583	84,94,75,308	90,04,21,237
Previous Year		168,86,01,051	10,50,29,852	3,77,58,417	175,58,72,486	76,75,50,045	6,51,86,568	-	83,27,36,613	92,31,35,873	92,10,51,006

RAMAN RESEARCH INSTITUTE, BENGALURU
SCHEDULES FORMING PART OF BALANCE SHEET AS AT 31ST MARCH 2021

(Amount in INR)

Schedule 9- Investments from Earmarked/Endowment Funds	Current Year	Previous Year
1. In Fixed Deposits		
RRI Pension Fund	10,71,64,250	10,26,64,250
RRI Provident Fund	8,43,74,503	8,98,12,551
Other Grants & Funds	12,51,00,000	3,74,00,000
2. Other Approved Securities	-	-
3. Shares	-	-
4. Debentures / Bonds	-	-
5. Retirement funds invested in SBI Life Insurance Limited	33,77,54,101	31,86,06,539
Claim (to be submitted) pending towards settlements made during the year	5,14,53,129	4,47,34,399
TOTAL	**70,58,45,983**	**59,32,17,739**

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



RAMAN RESEARCH INSTITUTE, BENGALURU

SCHEDULES FORMING PART OF BALANCE SHEET AS AT 31ST MARCH 2021

(Amount in INR)

Schedule 11- Current Assets, Loans & Advances	Current Year		Previous Year	
A. CURRENT ASSETS				
1. Inventories		5,95,537		6,83,440
2. Cash balances in hand (Including cash imprest)		17		300
3. Unused stamp value on Postal Franking Machine		94		8,620
4. Bank Balances				
Main Account	21,50,183		60,82,104	
Pension Fund Account	64,44,950		62,85,251	
Provident Fund Account	1,35,98,786		82,02,190	
Extra Mural Grants	11,95,248	2,33,89,167	2,09,83,033	4,15,52,578
TOTAL (A)		**2,39,84,815**		**4,22,44,938**
B. LOANS/ADVANCES AND OTHER ASSETS				
1. Advances and other amounts recoverable in cash				
On Capital Account				
a) Land	9,25,90,600		9,25,90,600	
b) Capital Assets	3,84,72,091	13,10,62,691	1,48,98,093	10,74,88,693
Deposits		35,53,990		33,53,632
Others		74,32,494		1,43,78,586
2. Income Accrued				
Main Account	5,91,204		4,62,022	
Pension Fund Account	6,98,585		36,59,128	
Provident Fund Account	37,87,586		77,36,991	
Extra Mural Grants	14,21,612	64,98,987	-	1,18,58,141
3. Claims Receivable				
Main Account	22,31,209		20,52,073	
Pension Fund Account	15,80,902		29,53,620	
Provident Fund Account	22,20,619		21,29,048	
Extra Mural Grants	31,33,887	91,66,617	16,71,265	88,06,006
TOTAL (B)		**15,77,14,779**		**14,58,85,058**
TOTAL (A+B)		**18,16,99,594**		**18,81,29,996**

S. Janardhan & Associates Chartered Accountants Bangalore 560 001

RAMAN RESEARCH INSTITUTE, BENGALURU

SCHEDULES FORMING PART OF INCOME & EXPENDITURE ACCOUNT FOR THE YEAR ENDED 31ST MARCH 2021

(Amount in INR)

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

Schedule 13- Grants/Subsidies	Current Year	Previous Year
1. Central Government		
Grants-in-aid		
i) Non-Plan	-	-
ii) Deferred Grant (To the extent of depreciation chargeable)	6,96,39,234	6,73,63,736
iii) Recurring	54,35,00,000	46,87,96,000
Total	**61,31,39,234**	**53,61,59,736**

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

Schedule 15- Income from Investments	Current Year	Previous Year
Interest on Investment from Earmarked / Endowment Fund	3,28,75,357	4,61,71,700
Less: Transferred to Earmarked / Endowment Fund	3,28,75,357	4,61,71,700
Total	-	-

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

Schedule 17- Interest Earned	Current Year	Previous Year
1) On Term Deposits		
a) With scheduled banks	-	-
2) On accounts with banks		
a) Attributable to Core grant funds **(transferable to Bharatkosh)**	25,28,635	17,85,815
b) Attributable to Own/other funds	32,70,409	56,34,849
3) On Loans/Advances		
a) Employees	83,754	1,26,229
Total	**58,82,798**	**75,46,893**

RAMAN RESEARCH INSTITUTE, BENGALURU

SCHEDULES FORMING PART OF INCOME & EXPENDITURE ACCOUNT FOR THE YEAR ENDED 31ST MARCH 2021

(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	1,51,45,694	76,75,314
Total	**1,51,45,694**	**76,75,314**

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	23,55,60,318	18,21,99,896
b) Allowances & Bonus	4,72,87,858	4,75,31,406
c) Contribution to NPS	57,58,442	58,93,498
d) Staff welfare expenditure	2,34,38,474	1,85,78,293
e) Retirement/Terminal benefits	12,36,07,110	9,30,21,792
Total	**43,56,52,202**	**34,72,24,885**

Schedule 21- Other administrative expenses	Current Year	Previous Year
1) Advertisement	7,55,000	8,51,068
2) Amenities	7,90,058	12,20,881
3) Audit Fee	53,100	70,800
4) Bank Charges	1,23,417	1,41,531
5) Campus Maintenance	2,45,92,671	1,95,47,199
6) Conveyance	4,45,238	5,04,049
7) Corporation Taxes	2,87,367	2,70,574
8) Creche	3,60,000	3,55,000
9) Electricity Charges	1,27,08,423	1,40,53,682

Continued on the next page

Schedule 21- Other administrative expenses (Continued)	Current Year	Previous Year
10) Entertainment & Hospitality	17,158	1,08,460
11) Freight	4,24,110	4,61,710
12) Honorarium & Professional Fee	74,97,836	83,82,086
13) Journal Subscription	33,51,326	43,66,687
14) Lease Rent (Gauribidanur)	5,57,510	5,12,200
15) Miscellaneous Expenses	9,26,778	12,29,483
16) Outreach	1,13,671	9,01,295
17) Patent Fee	5,57,362	10,79,611
18) Payroll Processing Charges	4,35,774	4,59,170
19) Ph.D Programme Expenditure	12,72,556	9,04,767
20) Postage & Courier Charges	64,596	1,29,610
21) Printing & Stationery	4,17,344	7,27,964
22) Repairs & Maintenance	1,18,72,312	1,08,16,059
23) Security Charges	80,11,108	83,57,186
24) Seminar/Conference	4,85,955	17,11,331
25) Stores & Consumables	3,12,51,594	4,40,87,939
26) Telephone & Communication	16,11,984	11,40,360
27) Travel Expenditure	10,66,573	60,00,321
28) Uniform & Livery	54,679	1,81,614
29) University Affiliation Fee	-	6,00,000
30) Vehicle Maintenance	19,41,686	28,24,275
31) Visiting Students Programme	5,38,206	38,11,898
32) Water Charges	7,62,913	7,67,588
Total	**11,33,48,305**	**13,65,76,398**

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
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Schedule-24

SIGNIFICANT ACCOUNTING POLICIES

1.	General	The Financial Statements have been prepared under the historical cost convention, on accrual basis of accounting and in accordance with generally accepted accounting principles. The presentation of final accounts is as per the Uniform Accounting Format for Central Autonomous Bodies as prescribed by Controller General of Accounts, Government of India
2.	Fixed Assets	Fixed Assets are stated at cost of acquisition that includes inward freight, duties, taxes and incidental expense to bring the asset to use. To confirm with presentation in the Uniform Accounting Format, advance payments for procurement of capital assets have been shown in Schedule-8 (fixed assets) Capital work-in-progress. No depreciation is charged on such items. Utilisation of grants received under the component, grants for Creation of Capital Assets is shown in Schedule-1 (Capital Fund). The value of assets, as stated in Schedule-8, is nett of depreciation.
3.	Depreciation	Depreciation is charged on **STRAIGHT LINE BASIS** at the following rates a. Buildings @ 1.63 % b. Capital Equipment, Canteen Infrastructure and Books @ 4.75% c. Computer & Peripherals @ 16.21% d. Vehicles @ 9.50% Depreciation is charged in the Income & Expenditure account. Full depreciation is charged on assets added before 30th September. Depreciation on assets added after 30th September is charged at 50%. In respect of asset blocks that end with a book value less than Re 1/- on applying depreciation, the book balance is closed with a notional value of Re 1/- by limiting depreciation charged to the notional book value.
4.	Inventory	Stock on hand, such as spares, stationery and consumables are valued at cost
5.	Government Grants	Grants received from Department of Science & Technology, Govt. of India under **SALARIES, GENERAL** and **CREATION OF CAPITAL ASSETS** is Accounted for as Core Grants. Grants with specific sanction for recurring expenditure is shown under Income & Expenditure Account. Unspent balance, which is nett of expenditure incurred during the year, is reported in the balance sheet under Schedule 1 (Grant Balances-Recurring Grant). Grants received for Creation of Capital Assets received during the year is added to the previous year's balance in the Balance Sheet. Unspent balance, which is nett of utilisation during the year, is shown under Schedule-1 (Grant Balances-Non Recurring Grant). Funds utilised to Create Capital Assets is shown as an addition in the Capital Fund as per AS-12. The Institute also receives Extra Mural Grants from various funding agencies. Such grants are shown as part of Schedule 3 (Earmarked / Endowment Funds).
	Foreign Currency Transactions	Transactions denominated in Foreign Currency are accounted for at the rates prevailing on the date of actual transaction. No provision is made to account for gains and losses arising out of exchange fluctuations.

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

Schedule-25

CONTINGENT LIABILITIES AND NOTES ON ACCOUNTS

A. Contingent Liabilities

1.	Claims against the Institute not acknowledged as debt	The Institute has established Letter of Credit favoring Oxford Instruments, towards procurement of High Resolution Atomic Force Microscope vide LC-0505321IM0000274. The LC would be retired in FY22
2.	Bank guarantees given by the Institute	NIL
3.	Disputed demands in respect of taxes	The Institute has reconciled the outstanding tax due on TRACES portal and resolved the same in FY 20-21. There are no outstanding claims against the Institute.

B. Notes on Accounts

1.	Current Assets, Advances & Deposits	Current Assets, Advances and Deposits have a value on realisation in the ordinary course of activities. The extent of realisation is equal atleast to the aggregate amount appearing in the Balance Sheet
2.	Employees' Retirement Benefits	a. Institute's contribution to the Provident Fund account are charged to Income & Expenditure Account of the institute
		b. As prescribed by the Govt. of India, the Institute has subscribed to Pension funds managed by SBI Life Insurance Company Limited, in respect of quantifiable liabilities of service benefits like Gratuity and Cash equivalent of Earned Leave. The Institute has also covered its liabilities for Commuted Value of Pension
		c. The amounts standing to the credit of the funds in SBI Life Insurance Company Limited are held in the name of the Institute in a fiduciary capacity. Balances appearing in the fund statements as at the close of financial year is shown under Schedule-3 (Earmarked/Endowment Funds-Retirement Funds). Interest earned, if any, during the year is treated as an Addition to the fund and reported accordingly in Schedule-3. Payouts on retirement on account of Gratuity, Cash equivalent of Earned Leave and Commuted value of Pension is through the fund.
		d. The institution has stopped further contributions to Retirement Funds since 2011 as the existing investments representing the retirement funds are earning interest. Evaluation of the adequacy of retirement funds is taken up once in 5 years and in that cycle, the evaluation will be carried out in the ensuing financial year. In view of this, no provision has been made during the year in respect of incremental liability, if any. Benefits are paid to the retiring employees out of the institutional funds. Institution treats the pay-outs as expenses of the year if the funds are not drawn by way of reimbursement from the retirement funds. As at 31-3-2021, there is a reimbursement amount pending in respect of retirement benefits paid during the year and is disclosed separately under the Investments from Earmarked Funds.

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

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

3. Advance for purchase of land

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

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

4. Funds of Core grants were kept in common bank account. Hence, the interest amount to be credited to Bharatkosh in compliance of rule 230(8) of GFR 2017 amounting to **Rs. 25,28,635/-** has been apportioned on the basis of monthly outstanding unspent grant balances

5. Schedules 1 to 25 are annexed to and form an integral part of the Balance Sheet as at 31st March 2021 and the Income & Expenditure Account for the year ended on that date.

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

As per our report of even date
For **M/s S. JANARDHAN & ASSOCIATES**
Chartered Accountants
FRN 005310S

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

(Sridhar S)
Director

(B. Anand)
Partner
M. No. 029146

BANGALORE / 05-07-2021

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