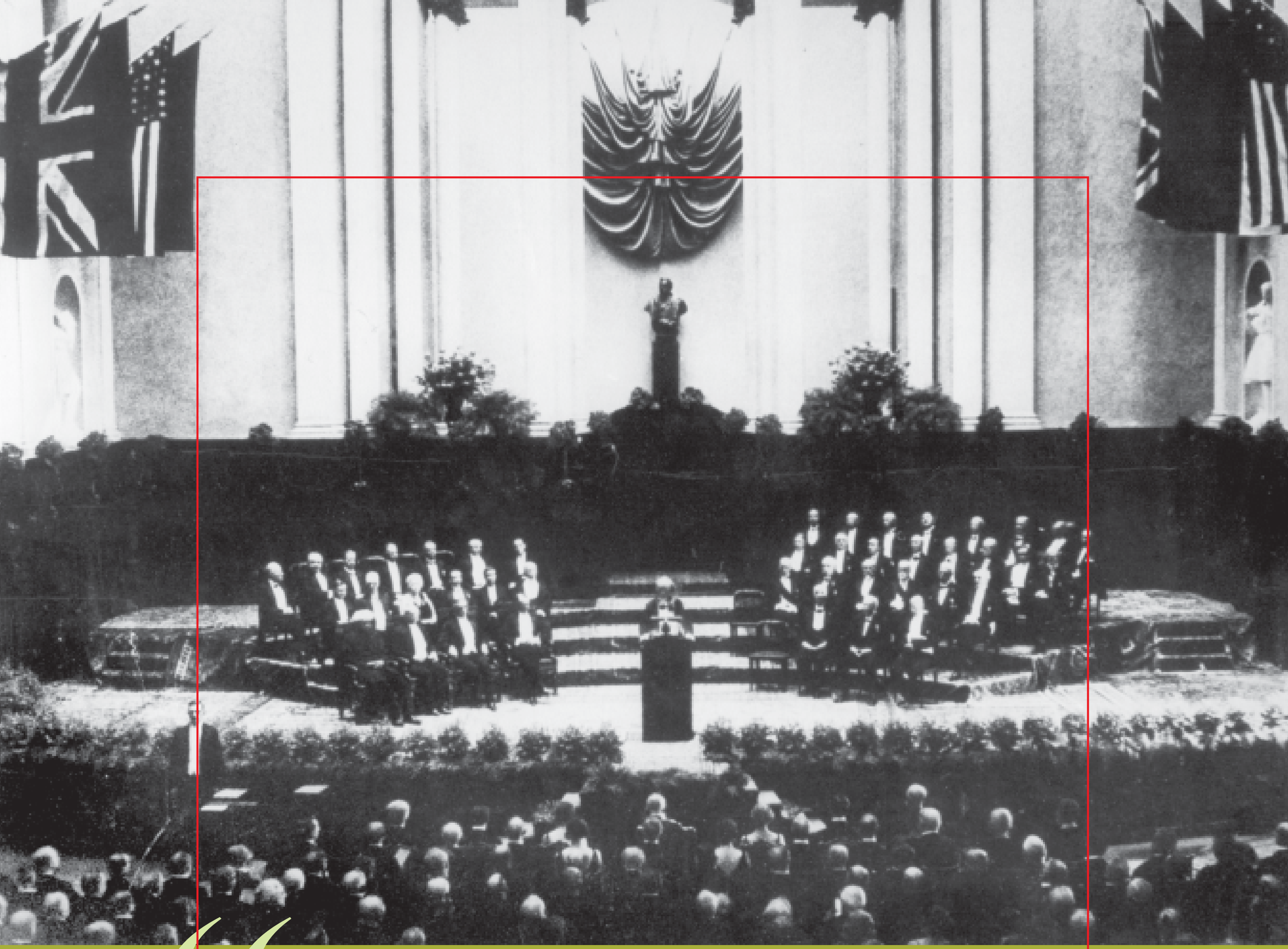
2010 ANNUAL REPORT 2011

RAMAN RESEARCH INSTITUTE BANGALORE

ANNUAL REPORT
2010 - 2011

Raman Research Institute
Bangalore



SCIENTIFIC RESEARCH IS FIRST AND FOREMOST AN EXPRESSION OF THE RESURGENCE OF THE HUMAN SPIRIT IN ITS SEARCH FOR SELF-EXPRESSION.
IT REPRESENTS THE RESPONSE OF THE MIND OF MAN TO THE MARVELLOUS AND EVER-CHANGING PANORAMA OF NATURE.

Sir C V Raman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FROM THE DIRECTOR

The annual report of the Raman Research Institute for the year 2010-11 is a summary of the research and academic activities of the Institute during the year.

The annual report presents synopses of the ongoing knowledge creation activities in the different research groups, many of which have outcomes in the form of publications in refereed scientific journals. The Institute considers the transmission of knowledge an important activity; this also includes the guidance of students for the conferment of PhD degrees as part of the PhD programme of the Institute, as well as the active Visiting Students Programme under which a number of students from all over the country visit the Institute for stays ranging from a few weeks to several months and participate in the many research activities of the Institute. Communications of the ongoing research and also a sharing of knowledge of current research – in professional talks given by members of the Institute in conferences and in external institutions as well as journal review talks at the institute – is another aspect of our knowledge diffusion. A cultural function of a premier research institute is the upholding and promotion of academic traditions and this includes the conduct of specialized seminars on technical topics targeted at specialized audiences as well as colloquia in a wider range of topics that are delivered in a style that strives to make current advances intelligible to a wider community. Additionally, outreach activities include writings intended for a lay and discerning audience as well as the delivery of motivational talks at educational institutions.

Included in this report are lists of publications in refereed journals, conference proceedings as well as in monographs, books and in popular periodicals, PhD degrees awarded during the period 01 April 2010 to 31 March 2011 as well as seminars and review meetings focused on current research, which were held at the Institute. The report also lists the scientists who have visited the Institute from within India and from overseas during the period.

Bangalore
August 31, 2011

Ravi Subrahmanyan
Director

A BRIEF HISTORY

Before jumping to the next pages in search of the current exciting research activities conducted at the Institute, take a few moments to read about its history. In between the collection of historical facts you'll discover a story about the power of basic human curiosity – the invisible foundation on which the Raman Research Institute was built and managed by its founder Sir C V Raman and subsequently by his successors.

In 1934, while still the director of the Indian Institute of Science (IISc), Raman started the Indian Academy of Sciences and attracted most of the best young scientists of that time, who published their work in world renowned journals of physics and chemistry. The same year the Maharajah of Mysore gifted to the Academy 11 acres of land in the north side of Bangalore. A few years later, Raman proposed that an independent research institute be built on that premises and an agreement with the Academy was signed.

Raman embarked on a number of long journeys throughout the country to raise funds for the new institute. In 1943, the collected sum, along with his personal savings, was allotted for the construction of the first building. Its initial completion coincided with the retirement of Sir C V Raman from IISc in 1948 and in the beginning of 1949 he shifted all his activities there. The new centre was named after its founder – Raman Research Institute.

From the very first moment of its foundation Raman undertook the management of his new institute with immense vigour and enthusiasm. He not only designed the main building with the help of an architect, but also took great interest in the arrangement of the whole premises. He planted trees, decorative bushes and flowers turning the barren land around into a beautiful garden. A walk in that garden was an indispensable part of his daily life. The initial staff in the new institute consisted of four people including Raman himself. The lack of electricity during the first two years didn't affect Raman's thirst for knowledge and understanding the wonders of Nature. Great scientific work was carried out during these years using a few lenses and a manually operated heliostat. In order to support his staff and expand the scientific activities at RRI, Raman who was unwilling to take money from the Government, started a couple of chemical industries along with one of his former students. He used the profit to pay his staff and equip his laboratories. In the years to come, the institute kept expanding – soon there was a new library, few other buildings and a museum holding Raman's personal collection of gems, crystals and minerals. Until his death in November 1970, Raman kept working tirelessly for the development and growth of the Raman Research Institute.

After his death, the Academy created a public charitable trust: the Raman Research Institute Trust. The lands, buildings, deposits, securities, bank deposits, moneys, laboratories, instruments, and all other movable and immovable properties held by the Academy for the Raman Research Institute were transferred to the RRI Trust. The foremost function of the RRI Trust was to maintain, conduct and sustain the Raman Research Institute. In 1972, the institute started receiving funds from the Department of Science and Technology of the Government of India which, since then, has been its main funding source. The same year, Venkatraman Radhakrishnan was invited to be the director of RRI. A renowned scientist himself, Radhakrishnan not only fulfilled C V Raman's desire to build an observatory at RRI but formed a strong group in Astronomy and Astrophysics whose research work today is regarded highly worldwide. Until the mid 90s, the two main areas of research were Liquid Crystals and Astronomy and Astrophysics. The constant growth of the Institute and the expansion of the research interests of its members led to the establishment of two new groups – Theoretical Physics and Light and Matter Physics. The Liquid Crystal group was renamed to Soft Condensed Matter which conveys more accurately the diverse research activities of its members.

Today, RRI research faculty, scientific staff and students conduct active research in the above mentioned four scientific fields inspired by the example of the founder – Sir C V Raman.

RRI AT A GLANCE

Mission

RRI is engaged in fundamental research in the areas of Astronomy, Astrophysics, Light and Matter physics, Soft Condensed Matter and Theoretical Physics as a part of the global endeavor of humanity to increase our knowledge and understanding of the world.

Director

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

Organization

RRI is an autonomous research institute. The supreme body of RRI is the RRI Trust. The director is the chief executive and academic officer. The Governing Council is the executive body responsible for the administration and management of the Raman Research Institute. The Finance Committee helps the Council with financial matters.

Location

RRI is located on a 20 acre plot in the north side of Bangalore City, the IT capital of India. It offers a quiet recluse from the bustling megapolis and a natural environment which is highly conducive to creative scientific work.

Research Areas

Astronomy and Astrophysics

Light and Matter Physics

Soft Condensed Matter

Theoretical Physics

Facilities

1. LABORATORIES

   A&A

   Radio Astronomy Labs:
   - a. Digital Signal Processing (DSP) Lab
   - b. RF and MM Wave Lab
   - c. X-ray Astronomy Lab

   LAMP

   Quantum Optics Lab
   Laser Cooling and Light Propagation Lab
   Quantum Interactions Lab
   Non Linear Optics Lab
   Laser-induced Plasma Lab

   SCM

   Chemistry Lab
   Physical Measurements Lab
   Liquid Crystal Display Lab
   Rheology and Light Scattering Lab
   X-Ray Diffraction Lab
   Biophysics Lab
   Electrochemistry and Surface Science Lab

   MECHANICAL ENGINEERING

   Mechanical Workshop
   Glass Blowing Facility

2. LIBRARY
3. COMPUTER FACILITIES
4. CAMPUS

Education

RRI offers the following academic programs:

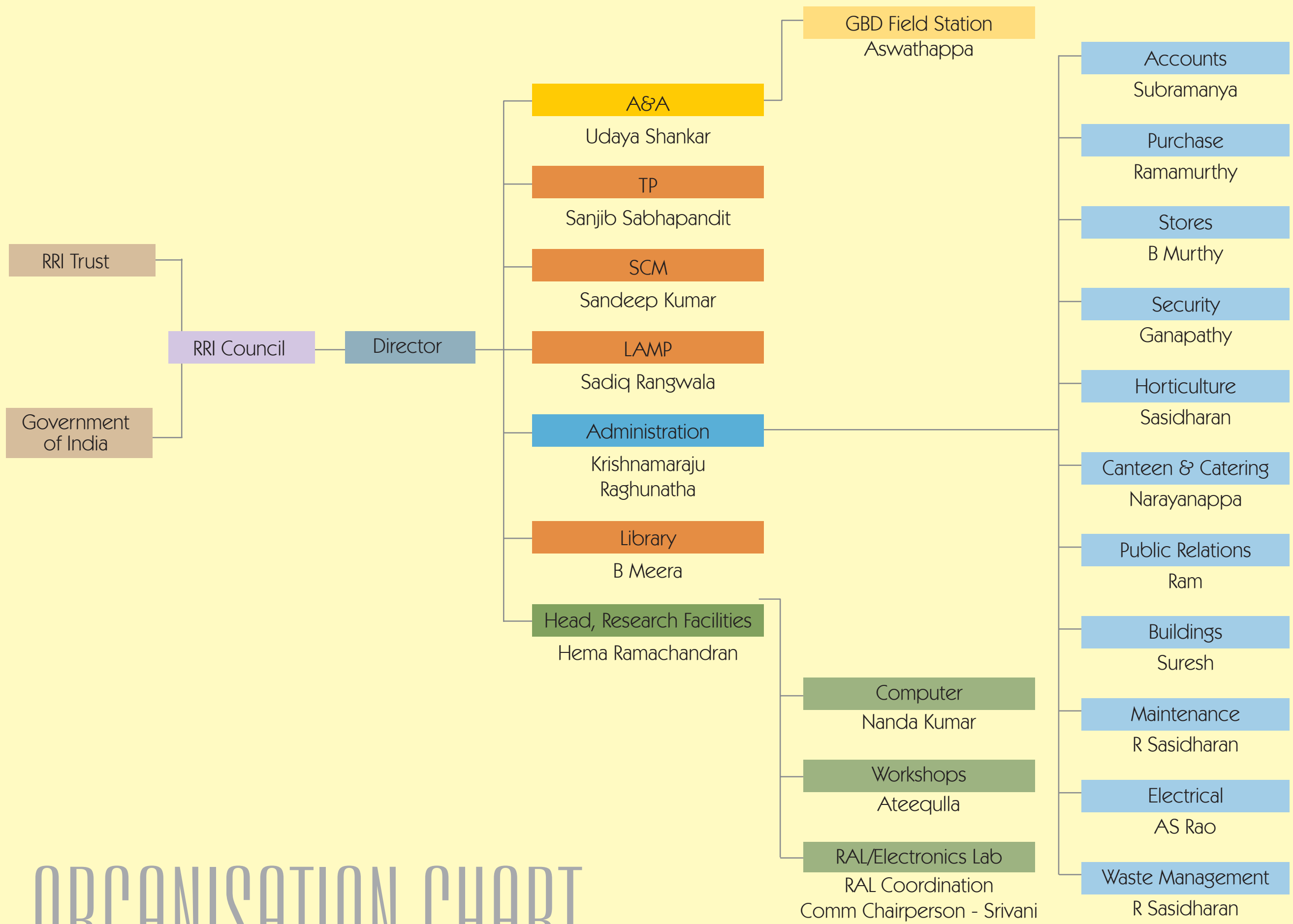
– PhD Program
– Post Doctoral Fellowship Programs
– Visiting Student Program

Funding

RRI is funded by the Department of Science and Technology, Government of India.

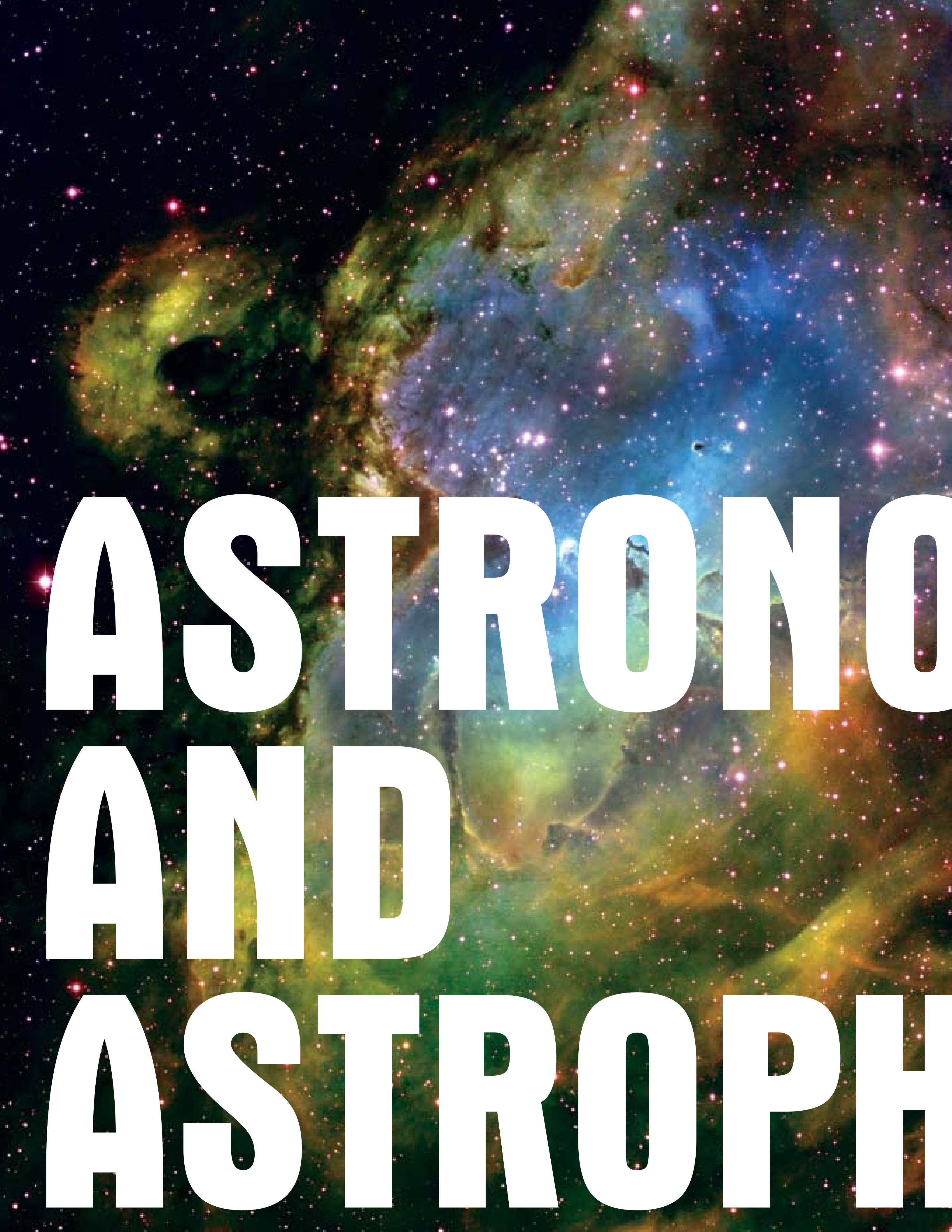
Research, Scientific/Technical, Administrative Staff and PhD Students

Research Faculty	43
Scientific/Technical	52
Administrative	27
PhD Students	53



ORGANISATION CHART

Journal Club	Supurna Sinha
Colloquia	Joseph Samuel, Pramod Pullarkat, Sadiq Rangwala
Hostel Warden	Biman Nath
Admissions Coordinator	Arun Roy
SAAC	Madan Rao
In-House Meeting	PhD students
JAP Rep of RRI	Shiv Sethi
Complaints Committee	KS Srivani (Chairperson), Marisa D'silva, Vrinda J Benegal, K Raghunatha, Madan Rao
Chairpersons of PhD Interview Committees	Reji Philip, Abhishek Dhar
Overseas Travel Committee	Sandeep Kumar (Chairman), Udaya Shankar, Madan Rao
Evaluation Committee	Joseph Samuel, Hema Ramachandran, Biman Nath, Abhishek Dhar, VA Raghunathan
Senior Management Team	Ravi Subrahmanyan, TN Ruckmongathan, Udaya Shankar, Joseph Samuel, K Krishnamaraju, K Raghunatha
Coordinator of Visiting Students Programme	Supurna Sinha
Coordinator of Summer Students Programme	Abhishek Dhar



ASTRONO
AND
ASTROPH

OVERVIEW

The Astronomy and Astrophysics (A&A) group at RRI comprises 30 motivated researchers who study the universe from its creation to its present state. The main areas of research include theoretical astrophysics, observational astronomy, astronomical instrumentation and signal processing.

Theoretical astrophysics concentrates on the development of analytical models and computational numerical simulations that try to describe the dynamics, physical properties and underlying phenomena of celestial objects (such as stars, planets, galaxies and interstellar medium, among others) as well as answer fundamental questions about the formation and evolution of the universe.

Observational astronomers use numerous telescopes built across the globe to study the radiation from space covering the entire electromagnetic spectrum – which ranges from low frequency (long wavelength) radio waves to very high frequency (short wavelength and extremely energetic) gamma rays. These observations form part of the information that is used to test existing theoretical models and offer new directions of study. Such studies have been the basis of our collective knowledge of the universe.

Telescopes have been used since the 17th century to study the universe. Today's highly sophisticated telescopes allow scientists to study celestial bodies in different frequency bands of the electromagnetic spectrum, and answer questions about the universe and its creation. RRI's astronomical instrumentation engineers are involved in the construction and operation of such telescopes around the world.

The following pages summarize the major areas of research for the A&A group as well as each member's individual work during the last year. This section will give the reader a more detailed and technical description of the members' respective research activities.

ASTROPHYSICS

Development of Cosmological Models: Cosmology is concerned with developing and testing physical models that try to explain the formation and evolution of the universe. Researchers at RRI are working on developing such models that describe radiation from the Epoch of Reionization (EOR). EOR refers to the period in the early history of the universe during which the emergence of the first luminous sources (such as stars and galaxies) ionized the predominantly neutral intergalactic medium. These models can provide important information about the process of structure formation in the universe and answer questions as to whether such radiation can be detected with existing telescopes.

Magnetohydrodynamic (MHD) Turbulence: Turbulence in electrically conducting fluids is a rarely observed phenomenon here on Earth. However, in galaxies, clusters of galaxies and the interstellar medium, where matter is ionized, it is a widespread phenomenon. Researchers at RRI are actively working towards the development of a comprehensive theoretical formulation of MHD turbulence.

Dynamo Theory: The astrophysics community at RRI conducts theoretical work to understand the origins of large magnetic fields around cosmic objects (stars, planets and galaxies) and the processes that sustain them. It is such magnetic fields that protect the Earth from the solar wind of particles that would otherwise destroy life on our planet.

Gravitational Dynamics: RRI researchers are also involved in the construction of models that describe the structure of the orbits of cosmic bodies around black holes. One of the ways of understanding gravitational lensing (the gravitational bending of light), which was predicted by Einstein, is by observing and studying the orbits of stars close to massive black holes.

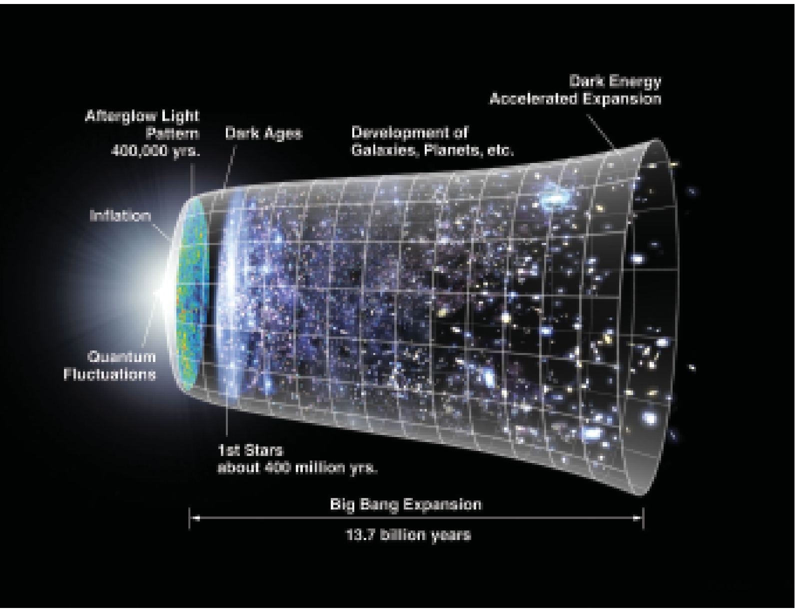
OBSERVATIONAL ASTRONOMY

Halo and Relic Radio Sources: Clusters of galaxies are the largest structures of matter in the universe. An understanding of their formation, structure and dynamics can bring important insights about their evolution. Halos and relics are structures within a galaxy cluster that emit strong radiation in the radio portion of the electromagnetic spectrum. Various models exist that attempt to explain the origin of this radiation. Currently, researchers at RRI compare observational data from the radiations of radio galaxies with AGN have shown that some are slowly dying out. How many such galaxies stay invisible to us because of the limitations posed by the sensitivity of today's telescope receivers and what brings about the end of AGN are some of the questions that concern researchers at RRI.

HI Regions in the Milky Way Interstellar Medium: After the Big Bang, some 13.7 billion years ago, hydrogen was created in great quantities in the universe making it the basic building block of stars. The space between stars is filled with neutral hydrogen at extremely low densities compared to the air we breathe on Earth. The emissions from these hydrogen regions – called HI regions – carry information about the conditions before star formation. Researchers at RRI look at the formation and structure of such HI regions using observational data from various radio telescopes in India and abroad.

Pulsars: The detection of pulsars was a serendipitous discovery. Pulsars are neutron stars that originate in supernovae and spin very fast due to the conservation of angular momentum and periodically emit radio waves. Because of their periodic emission, pulsars are often called "the lighthouses of the universe". We can only observe pulsars that beam in the direction of Earth. Pulsar emissions provide insight about their structure and distance. They are also a wonderful experimental platform to test general relativity. Today, millisecond pulsars are one of the most accurate clocks that have been found in the universe. RRI continues to conduct active research on pulsars and develop receivers that could reveal further details about their nature.

Lifecycle of Radio Galaxies: As radio telescopes become increasingly sensitive and of greater resolution, intricate features and morphologies of and within radio galaxies can be observed. A particular type of galaxy, called restarting radio galaxies, has captured the interest of researchers at RRI. It is believed that activity in the nucleus of the galaxy had stopped and then started again fresh. Such a scenario would explain the observations made and provide a useful input to our understanding of the evolution and lifecycle of radio galaxies. Why did the nucleus die, how long was it dead before it restarted its activity, what are the mechanisms that triggered its rebirth – those are some of the questions RRI astronomers are trying to answer in collaboration with Indian and international colleagues.



Radio Galaxy Morphologies: In recent years, X-shaped radio galaxies have caught the interest of the astronomy community, and members of the A&A group at RRI are active participants in this research field. In X-shaped radio galaxies, the typical two lobes are accompanied by two others to form a radio galaxy whose lobes look like the letter X. Two of the lobes are active while the other two are dead. Theories compete to explain how the two additional lobes are generated. Current observations at RRI are used to test these theories and deepen our understanding of X-shaped radio galaxies.

INSTRUMENTATION – DESIGN AND DEVELOPMENT

RRI is involved in the design and development of several telescopes across the world.

Most current antenna systems are based on large reflectors with a single or a small number of feeds. The Murchison Widefield Array (MWA) and LOFAR prototypes have heralded a paradigm shift in the design of next generation of radio telescopes. Science projects like EOR and transients have pushed the interesting range of frequencies for many next generation radio telescopes to less than a GHz with significantly improved sensitivity with large bandwidths and large field of view. This can be realized with a phased array or Aperture Array (AA), where the number of beams depends only on the available processing power and available communications.

RRI has accumulated expertise in this field with its involvement in Guaribidanur Radio telescope, Mauritius Radio Telescope, MWA and development of broadband feed for Greenbank Radio Telescope.

With this background, the institute has embarked on a programme to develop the Aperture Array technology in the frequency range 50 to 1000 MHz and has initiated design process for an RRI Aperture Array telescope prototype. With this motivation, RRI has initiated development of

1. A broadband antenna capable of operating over the frequency range 50 to 1000 MHz.

2. A low noise signal conditioner chain with sufficient amplification to digitize signals from a broadband antenna.

3. A high speed digitizer (10 data bits with a 2 GHz sampling rate) and a data aggregation board.

To facilitate design, RRI carried out on a small scale interference monitoring campaign in GBD and Bangalore, and initiated discussion with Texas Instruments to design a single chip signal conditioner followed by a high speed analogue to digital converter. The present status has been summarised in two short technical reports. The design and development of high speed A to D converter and data aggregation cards are under progress.

Mauritius Radio Telescope (MRT): MRT was built in the late 1990s in Bras d'Eau at the north-east side of Mauritius, as a joint effort by RRI, Indian Institute of Astrophysics and University of Mauritius. It is a T-shaped 2x1 km aperture synthesis array that observed the sky at 151.6 MHz in the declination range of -70° to -10°. The scientific objectives of MRT are to produce radio surveys of the southern sky, observe and study pulsars, solar radio emission, extragalactic radio sources, supernova remnants and steep spectrum sources. In the new phase of MRT data analysis, the group had re-established the array geometry (an error of 1mm/m was established) which weeded out systematics in the position of sources in the MRT images, generated new calibration tables and new PSFs for deconvolution and also developed field-of-view calibration. With these new developments the group has been able to complete imaging of an additional steradian of the sky covering the declination range -70° to -10° and the sidereal hour range 00hr to 06hr. Imaging the sidereal hour range 07 hr to 18 hr is under progress.

The data analysis for the RA range 07 to 18 hr has met with certain difficulties. The problems faced are twofold: At the first level the quality of data for these RA ranges are very poor. This leads to incomplete (uv) coverage and leads to very poor dynamic range images, especially in regions close to the galactic plane. In addition, a good consistent flux density calibration for the four delay zones has not been possible. Work is in progress to overcome these problems.

In the mean time, the Institute has started cataloguing extended sources seen in MRT survey. Cross identification of around 300 sources listed as extended in the 843 MHz images made using the Molongo Observatory Synthesis Telescope (MOST), reported by Jones and McAdam has been carried out. More than 100 common sources have been identified. Similarly along the galactic plane around

thirty and odd extended SNRs have been identified using Green's catalogue. A thorough investigation of flux-calibration and positions of these features is underway.

Giant Meterwave Radio Telescope (GMRT): GMRT is the largest low frequency telescope in the world. The collaboration between Tata Institute of Fundamental Research (TIFR), Mumbai, which currently operates the telescope, and RRI has been a long tradition. RRI has previously developed receivers in the 20-cm band as well as specialized receivers for pulsar observations that have been installed in GMRT to improve its observational capabilities. Currently, researchers and students at RRI are developing 50 MHz high sensitive receivers for the telescope. Such receivers have been installed on four of GMRT's antennas. After extensive testing, a proposal has been submitted for the fabrication and installation of these receivers on all 30 antennas to carry out an all-sky survey at 50 MHz with unprecedented sensitivity and resolution in the low frequency regime. Low frequency surveys allow for statistical analysis of astronomical objects with high redshifts and also provide foreground information crucial for studies of the EOR.

Wideband Receivers on the Green Bank Telescope: Researchers at RRI have developed a wideband multi-channel receiver for pulsar observations that was recently installed in the largest single dish telescope in the world – the Green Bank Telescope in West Virginia, USA. The receivers allow for high-time and spectral resolution of pulsar emissions. Data from the observations is currently being analyzed.

Decameter Wave Radio Telescope at Gauribidanur: The decameter wave radio telescope at Gauribidanur (80 km north of Bangalore) was built and is operated by RRI and Indian Institute of Astrophysics. This is a 1.4 km (E-W wing) by 0.5 km (South wing) T-shaped array consisting of 1,000 dipole antennas. Radio emissions from the sun's corona and various radio sources at 34.5MHz have been observed using the telescope. RRI researchers are currently analyzing pulsar data collected using the E-W wing of the telescope.

Murchison Widefield Array (MWA): MWA project is an international effort to design and build a novel low-frequency radio telescope to observe signals from the Epoch of Reionization, measure the heliospheric plasma and conduct a high sensitivity survey of the dynamic radio sky. The MWA will consist of 8,000 dual-polarization dipole antennas optimized for the 80-300 MHz frequency range, arranged as 512 "tiles", each a 4x4 array of dipoles. A test bed of 32 tiles have already been deployed in the radio-quite zone near the town of Geraldton in Western Australia, providing the first sets of data from the instrument. RRI is a full partner in this project along with US and Australian institutions. Engineers and scientists from the A&A group have designed, built and tested the digital receivers and data processing electronics for the MWA telescope. Currently, they are looking at data collected with the 32-tile test bed in an attempt to understand the efficacy of different observing, calibrating, and data processing strategies for the detection of signals from the EOR.

3m submm wave telescope prototype (3mSTeP): Members of the A&A group are currently involved in the hardware development of a 3m submm wave telescope which would serve as a prototype for the development of a 30m telescope. The construction of a telescope at this frequency would allow researchers to study interstellar clouds and dust, where stars and galaxies are formed and where mm and submm waves travel unabsorbed. Observations would also bring valuable information about the cosmic microwave background (CMB), the afterglow of the enigmatic gamma ray burst, star formation processes at high redshift and many more.

However, the major problem at these frequencies is the Earth's atmosphere which is opaque for most of the band. That requires telescopes to be deployed at high altitudes in order to minimize the travel of submm waves through the atmosphere. Members of the A&A group are currently involved in the hardware development of a 3m submm wave telescope which would serve as a prototype for the development of a 30m telescope. They have already resolved challenges in the mechanical design of the dish and the development of an energy efficient motor system needed for the remote deployment where power grid doesn't reach. The group is currently working on the construction of very broadband 8GHz spectrometers needed for the telescope receiver system.

X-ray Polarimeter: The A&A group has expanded its observations beyond radio and mm waves to the X-ray region of the spectrum. RRI has built a fully equipped lab for fabrication and testing of X-ray detectors and currently, researchers are working on the development of an X-ray polarimeter sensitive in the energy range of 5-30 keV. The instrument will be launched in to space in collaboration with ISRO. The PI of the project says: "The X-ray astronomical research and in a broader context, high-energy astrophysics research will be strongly enriched from X-ray polarisation measurements of many kinds of astrophysical objects. In absence of any X-ray polarisation mission presently approved anywhere in the world, the proposed experiment will be the pathfinder of future, more sensitive experiments are required." Earth's atmosphere completely absorbs photons in the X-ray and gamma-ray band. Therefore, observations of X-ray sources can be carried out only from space platforms like balloons, rockets, or satellites. To achieve a reasonable sensitivity, the proposed experiment requires very long observations of bright X-ray sources that are only possible from a satellite.

ASTROSAT is the name given to Indian Space Research Organization's (ISRO) satellite mission for multi-wavelength astronomy scheduled to be launched in a 650 km near equatorial orbit in 2011. Its major scientific goals include:

(i) simultaneous multi-wavelength monitoring of intensity variations in a broad range of cosmic sources;

(ii) broadband spectroscopic studies of X-ray binaries, AGN, clusters of galaxies and stellar coronae;

(iii) sky surveys in the hard X-ray and UV bands;

(iv) studies of periodic and non-periodic variability of X-ray sources and more. ASTROSAT will carry five astronomy payloads for simultaneous multi-band observations. RRI is currently involved in the development of Large Area X-ray Proportional Counter (LAXPC) for X-ray timing and low-resolution spectral studies over a broad energy band. One of the payloads on ASTROSAT will consist of three LAXPCs.

ONGOING RESEARCH

The areas of scientific exploration for N Udaya Shankar include sky surveys, detection of EOR, aperture arrays and instrumentation and signal processing for radio astronomy.

Udaya Shankar manages the Murchison Wide Field Array (MWA) project, both in his capacity as Member of the MW Board and as Deputy Project Manager (India). One of the main science goals of this array is to detect signal from the EOR. In collaboration with Harish Vedantham and Ravi Subrahmanyan, he studied imaging modes and strategy for MWA to detect EOR. As a first step, appreciating that limiting the confusion from galactic and extragalactic foregrounds is critical to the success of MWA, the frequency structure of the three dimensional point spread function (PSF) of MWA is being studied. The 3D PSF has the peculiar property that structures in the two angular dimensions get coupled to frequency axis, which maps the Line of Sight (LOS) distance. A formalism to estimate the foreground contamination along frequency, or equivalently LOS dimension, and establish a relationship between foreground contamination in the image plane and visibility weights on the Fourier plane is being estimated. Two dominant sources of LOS foreground contamination have been identified by Udaya Shankar and his collaborators – "PSF contamination" and "gridding contamination". Their research showed that a judicious choice of the frequency window function can minimize coupling of angular structures in PSF to the frequency axis. They are also looking at the role of imaging algorithms in minimizing the stochastic noise in the 3D PSF due to gridding.

Udaya Shankar is also working on the development of aperture array technology and prototyping for an RRI Aperture Array telescope in collaboration with AA Deshpande, Ravi Subrahmanyan, Srivani, Somashekar, and members of RAL. Udaya Shankar and his collaborators from RRI and RAL are also developing Aperture Array technology in the frequency range 50 to 1000 MHz and have initiated design process for an RRI Aperture Array telescope prototype.

Work continued on the previous year's all-sky survey at 150 MHz using the Mauritius Radio Telescope (MRT). In the new phase of MRT data analysis, Udaya Shankar and his collaborators re-established the array geometry (an error of 1mm/m was established) which weeded out systematics in the position of sources in the MRT images, generated new calibration tables and new PSFs for deconvolution and also developed field-of-view calibration. These new developments have enabled the complete imaging of an additional steradian of the sky.

The cataloguing of extended sources seen in the MRT survey has also begun. Cross identification of around 300 sources listed as extended in the 843 MHz images made using the Molongo Observatory Synthesis Telescope (MOST), reported by Jones and McAdam has been carried out. More than 100 common sources have been identified. Similarly along the galactic plane, around 30 extended SNRs have been identified using Green's catalogue. A thorough investigation of flux-calibration and positions of these features is underway.

KS Dwarakanath's research interests lie in the fields of extragalactic astronomy, clusters of galaxies, halo and relic radio sources, the galaxy and interstellar medium. His work during the year has been largely focused on halo and relic radio sources.

Radio halos and relics are believed to be associated with cluster mergers, although not all merging clusters host them. The X-ray surface brightness distributions of merging clusters typically exhibit non-concentric iso-intensity contours, small-scale structures, multiple peaks and/or poor optical and X-ray alignments. The aim of the MAssive Cluster Survey (MACS) is to compile a statistically complete sample of very X-ray luminous (and therefore massive) distant clusters of galaxies in the redshift range of 0.3 to 0.6. Along with Siddharth Malu and Ruta Kale, Dwarakanath has imaged six of the hottest and most luminous clusters selected from the MACS at 230 MHz and 610 MHz using the GMRT. All the clusters chosen had disturbed X-ray morphologies, implying that they may have undergone mergers. Of the six cluster fields, four exhibited diffuse and filamentary radio emissions likely to be of cluster origin. The most spectacular radio halo was discovered in the second brightest cluster in the sample: this radio halo extended along the North-West, similar to the morphology of the X-ray emission confining the halo emission. The 1400 MHz radio luminosity of the halo is in agreement with the value expected from the Lx-Lr correlation for cluster halos. Dwarakanath and his colleagues are studying the implications of these detections.

Dwarakanath and **Ruta Kale**, in collaboration with Joydeep Bagchi and Surajit Paul of the Inter-University Centre for Astronomy and Astrophysics (IUCAA), Pune, have also been studying ring-like double radio relics in the merging, rich galaxy cluster A3376 to better understand non-thermal phenomena at cluster outskirts. This study has produced the first low frequency (330 and 150 MHz) images of the double relics using the GMRT. With the help of the GMRT

330 MHz map and the existing VLA 1400 MHz map, the distribution of spectral indices over the radio relics have been constructed and analyzed. The researchers found flat spectral indices at the outer edges of both the relics and a gradual steepening of spectral indices toward the inner regions, thereby supporting the model of outgoing merger shock waves. The eastern relic showed a complex morphology and complex spectral index distribution toward the inner region. This is an area of study that is being looked into in the context of the effect of large scale accretion flows on the outgoing merger shocks as per recent simulations.

Radio relics in galaxy clusters can be produced by electrons accelerated at cluster merger shocks or by adiabatically compressed fossil radio cocoons or by dying radio galaxies. The spectral evolution of radio relics is affected by the pressure of the surrounding thermal plasma. Dwarakanath and Ruta Kale also presented a low frequency study of three radio relics present in the environments of dense cluster core (A4038), in the cluster outskirts (A1664) and in the filaments (A786). Multi-frequency – three or more frequencies in the range 150-1400 MHz – imaging of these relics indicates the following:

- The spectral indices of the relics progressively steepen as the environment becomes denser, i.e., relics in rarer environments have flatter spectra compared to relics at the cluster centre. Similarly the sizes of the relics range from _ 200 kpc to _ 1.6 Mpc as one goes from denser to rarer environments. This is consistent with the expectation of steepening of the spectral index due to the confinement of the relativistic plasma by the intra-cluster medium.
- Low frequency images from GMRT of the relic in A4038 led to the discovery of steep spectrum emission much larger in extent than was known from 1400 MHz images.
- Best fits to the integrated spectra of these relics in the framework of the adiabatic compression model were obtained. The spectrum of A4038 relic can be best fit by a model of adiabatically compressed plasma. The spectra of relics in A1664 and in A786 are best fit by a model of a fossil radio galaxy.
- Spectral index maps of all the three relics do not show any obvious gradients indicating the absence of shocks in these systems.

Biman Nath's research interests lie in the field of cosmology, structure formation and extragalactic astronomy. X-ray observations of intracluster medium (ICM) gas have shown that there is a universal pressure profile of the gas. Nath's research activities during the year included using this gas pressure profile to determine the entropy injected into the ICM, with the aim of shedding light on the possible evolution of the entropy injection. The gas profile was compared with the profile expected in the absence of any entropy injection. With data collected by S Majumdar of TIFR, it was found that there exists a simple scaling of the entropy injection with the cluster mass. The results of this study indicate, for the first time, that the entropy injection decreases with increasing redshift. This paper has been accepted in MNRAS.

Nath has continued his research work on galactic outflows with radiation pressure. It has been observed that the maximum speed of clouds embedded in galactic outflows is 2-3 times the rotation speed of disc galaxies. In collaboration with PhD student Mahavir Sharma and Y. Shchekinov of Southern Federal University in Russia, Nath explained this phenomenon analytically by calculating the terminal speed of winds from disc galaxies that are driven by radiation pressure on dust grains. This paper has been published in ApJ Letters.

Avinash A Deshpande's activities during the year included further analysis of the 12-hour synthesis OH-line data in the direction of W49N from VLBA to better understand the significant scattering due to the intervening interstellar medium. Detailed high angular-resolution images at 1612, 1665 and 1667 MHz revealed scattered broadened OH spots (a few tens of milli-arc-seconds in size), indicating not only anisotropic scattering (axial ratios between 1.5 to 3) with the position angles of the spot images oriented perpendicular to the galactic plane and angular broadening being much smaller than reported by earlier studies, but also significant differences in scatter broadened images for the two hands of polarization. These differences suggest that there might be significantly different scattering screens sampled by the two polarizations, as would be expected in principle, in the presence of magnetic field along the sightline. This work was in collaboration with W. M. Goss from NRAO, R. Ramachandran from San Jose, Jose E. Mendoza-Torres from Instituto Nacional de Astrofisica, Optica y Electronica (Mexico), and Tanmoy Laskar from Harvard University.

Also being analyzed are pulsar observations made in 2009 using the multi-band receiver with GBT. Related developments includes implementing second phase firmware to enable online spectral and Stokes parameter computation and integration, and exploring/testing alternative solutions for an improved method to record data, aimed to reduce possible slips (missing packets), as well as testing a log-periodic array element for use in the GBT multi-band feed. People involved include C Vinutha, Jayanth Channamagalam of University of West Virginia, Durai Chelvan, and project students S. G. Sahana and Nandan Roy.

Attempts were made to extract large-scale distribution of cold HI in the Milky Way in collaboration with Gauri Kulkarni of Pune, John Dickey of the University of Tasmania and Snezana Stanimirovic of the University of Wisconsin-Madison.

In the estimated structure functions for both HI emission and optical depth, the galactic spiral structure shows its imprint, and the emission data serves as a reference set in revealing that signature exclusively, wherein the correlations between the spiral arm and inter-arm regions, and arm-to-arm result in significant modulation. Similar modulation was also seen in the structure function for the opacity (optical depth). However, it seems to significantly level-off beyond a few 100 pc, if not around 100-pc scale. This is suggestive of an outer-scale for coherent structure in opacity on the scales of shell and super-shells.

In collaboration with Richard Dodson from ICRAR (Australia) and Dave McConnell of ATNF (Australia) the radio nebula that surrounds the X-ray PWN emission imaged by Chandra Observatory was studied some years ago at high frequencies using the ATCA. As a follow-up, full-Stokes imaging of the radio nebula using GMRT at 610 and 1420 MHz was proposed to study its evolution with frequency. The data for the first run of these observations (made by the team including Richard Dodson and Wasim Raja) are being analyzed using a DiFX correlator setup with cluster computing at ICRAR, including off-line binning of the data on the pulsar phase.

Development of a suitable spectral analysis pipeline to process time-sequences from X-ray binaries, as a preparatory step to study QPOs, is undertaken. The software, on which initial tests are being conducted, allows flexible extraction, calibration and reduction of data, usually acquired with several detectors. This study is in collaboration with Harsha Raichur of IUCAA and Nishant Singh.

Ravi Subrahmanyan's research during the year was focused on the epoch of reionisation.

He studied the mechanisms by which foreground radio sources on the sky contaminate attempts to image the red-shifted 21-cm signals from the EOR. The contamination was shown to be separable into a PSF contamination component that originated via the leakage of sources through side-lobes of the synthetic point spread function of the interferometer telescope, and a gridding contamination component that was caused by the imaging algorithm commonly used in Fourier synthesis imaging. The study led to devising methods by which confusion-free regimes may be created via a transformation to a domain

where the contamination may be confined and separated from the EOR signals. Numerical simulations of the effects of contamination supported the analytic work and the efficacy of the proposed methods was demonstrated. This work was in collaboration with Harish Vedantham and N Udaya Shankar.

Subrahmanyan, along with A Raghunathan, Nipanjana Patra and Udaya Shankar, is developing systems for the measurement of all-sky averaged radio spectrum in the frequency range 87.5-175 MHz so as to measure the all-sky signatures from the EOR. Both interferometer methods and single element systems have been deployed at the Gauribidanur field station and the system performance is being analysed and developed further.

Biswajit Paul's research activities during the year included developmental work for an X-ray polarimeter and ASTROSAT and the investigation of various aspects of compact X-ray sources.

He has been working on developing an X-ray polarimeter for a future small astronomy satellite mission. X-ray polarisation measurement is a still-unexplored area and has strong potential for understanding several important high energy astrophysics problems.

X-ray polarisation measurement is a unique tool that may provide crucial information regarding the emission mechanism and the geometry of various astrophysical sources, like neutron stars, accreting black holes, pulsar wind nebulae, AGNs, and Supernova Remnants, and can help probe matter under extreme magnetic fields and extreme gravitational fields. Although the three other domains of X-ray Astronomy – timing, spectral and imaging – are well developed, there has been very little progress in X-ray Polarimetry with only one definitive polarisation measurement and a few upper limits available so far. A proposal for a scattering polarimeter has been submitted to the Indian Space Research Organization (ISRO) for a dedicated small satellite mission and a laboratory unit has been built.

The work carried out at RRI includes the following:

- Fabrication of an engineering model of the X-ray polarimeter; the detector and collimator design has been completed.
- A mechanical analysis of the engineering model of the detector system has been carried out.
- Fabrication of two detector units has started. Assembly of one of these detectors is in progress.

- Position determination of the X-ray events by the charge division method has been accomplished. This technique has been tested successfully in a rectangular detector and a cylindrical detector.
- Design and test of the front end electronics has been completed. Engineering model fabrication of the front end electronics is to start soon.
- Design and development of the processing electronics and the common electronics units are in a very advanced stage.

PV Rishin, MR Gopalakrishna, R Duraichelvan, CM Ateequlla and members of RAL and MES have contributed to these progresses.

In collaboration with ISAC, Bangalore, and SAC, Ahmedabad, Paul worked on the development of the ASTROSAT-LAXPC data reduction software. He is also LAXPC representative in the ASTROSAT Ground Segment Committee that will take care of all ASTROSAT activities other than hardware development and Astrosat Calibration Committee.

The year gone by has seen significant contributions in the areas of orbital evolution studies of X-ray binaries; quasi-periodic oscillations in accreting pulsars and black holes; and complex pulse phase and orbital phase dependence of broadband X-ray spectrum in accreting pulsars, among others. A summary of these studies follows.

Radiation from accreting black holes in their thermal dominated (High Soft) state is expected to be polarised due to scattering in the plane parallel atmosphere of the disk. Also, special and general relativistic effects in the innermost parts of the disk predicts energy dependent rotation in the plane of polarisation and some distinct signatures which can be used as a probe for measuring the parameters of the black hole like its spin, emissivity profile and the angle of inclination of the system. An analysis of expected minimum detectable polarisation was carried out from some of the galactic black hole binaries GRO J1655-40, GX339-4, H1743-322, Cyg X-1 and XTE J1817-330 in their thermal dominated state with a proposed Thomson X-ray Polarimeter. Along with the measurement of the degree of polarisation, the polarisation angle measurement is also important, and hence the error in the polarisation angle measurement for a range of detection significance was also obtained. This analysis was carried out in collaboration with Chandreyee Maitra from RRI.

Paul and Chetana Jain of Delhi University carried out an X-ray eclipse timing analysis of the transient low mass X-ray binary XTE J1710-281. They reported observations of 57 complete X-ray eclipses, made with the proportional counter array detectors aboard the RXTE satellite. Using the eclipse timing technique, they derived a constant orbital period. Two instances of discontinuity were also discovered in the mid-eclipse time, one before and one after the above MJD range. These results are interpreted as three distinct epochs of orbital period in XTE J1710-281. The only other X-ray binary with unambiguous detection of orbital period glitch is EXO 0748-676.

4U 1822-37 is a Low Mass X-ray Binary (LMXB) system with an Accretion Disk Corona. 16 new mid-eclipse time measurements of this source have been obtained during the last 13 years using X-ray observations made with the RXTE-PCA, RXTE-ASM, Swift-XRT, XMM-Newton and Chandra observatories. These, along with the earlier known mid-eclipse times, have been used to accurately determine the timescale for a change in the orbital period of 4U 1822-37. X-ray pulsations from the source were also detected. In view of these results, Paul and Chetana Jain have put forth various mechanisms that could be responsible for the orbital evolution in this system. Using the long-term RXTE-ASM light curve, it was found that the X-ray intensity of the source has decreased over the last 13 years by ~40% and there are long-term fluctuations at time scales of about a year. In addition to the long-term intensity variation, significant variation in the intensity during the eclipse has also been observed.

Jincy Devasia and Marykutty James from MG University in Kottayam and Biswajit Paul carried out a detailed timing and spectral analysis of Rossi X-ray Timing Explorer Proportional Counter Array (RXTE-PCA) data obtained from observations during the outburst of a transient X-ray pulsar 1A 1118-61 in January 2009. The pulse profile showed significant evolution during the outburst and also significant energy dependence – a double-peaked profile up to 10 keV and a single peak at higher energy. Quasi-periodic oscillations (QPOs) at 0.07-0.09 Hz were also detected. The magnetic field strength calculated using the QPO frequency and the X-ray luminosity was found to be in agreement with the magnetic field strength measured from the energy of the cyclotron absorption feature detected in this source. The 3-30 keV energy spectrum over the 2009 outburst of 1A 1118-61 was well fitted with a partial covering power-law model with a high-energy cut-off and an iron fluorescence line emission. The pulse phase resolved spectral analysis showed that the partial covering and high-energy cut-off model parameters have significant changes with the pulse phase.

Paul, Devasia and James also made a detailed investigation of the timing and spectral properties of the transient X-ray pulsar GX 304-1 during its outburst in August 2010, using observations carried out with the RXTE-PCA satellite. They detected strong intensity and energy dependent variations in the pulse profiles during the outburst. The pulse profile showed significant evolution over the outburst. It showed complex structures consisting of a main peak with steps on both sides during the start of the outburst. On some days, a sharp dip like feature was seen which disappeared at the end of the outburst; when the profile evolved into a sinusoidal shape. At low energies, the pulse profiles appeared complex, consisting of multiple peaks and a narrow minimum. The amplitude of the second brightest peak in low energies decreased with energy, and above 12 keV, the shape of the pulse profile changed to a single broad peak with a dip like feature. The dip had energy dependence, both in phase and in width. QPOs were detected at 0.125 Hz with a harmonic. The QPO feature had a low rms value of 2.9% and it showed a positive energy dependence up to 40 keV with the rms value increasing to 9% at 40 keV. The QPO frequency decreased from 0.128 Hz to 0.108 Hz in 12 days. As before, the 3-30 keV spectrum could be well fitted with a partial covering power-law model with a high energy cut-off and iron fluorescent line emission. For a few of the observations carried out during the decay of the outburst, the partial covering absorption component was found to change to single component absorption. The partial covering and high energy cut-off parameters varied significantly with the pulse phase.

After a long quiescence of three decades, the transient X-ray pulsar 4U 1901+03 became highly active in February 2003. The analysis of RXTE-PCA observations of this source showed several interesting features like X-ray flares, a broadening of the pulse-frequency feature, and QPOs. The X-ray flares showed spectral changes, had a duration of 100-300 s, and were more frequent and stronger during the peak of the outburst. During the outburst, Paul, Marykutty James and Jincy Devasia also detected a broadening of the pulse-frequency peak as well as intensity-dependent changes in the pulse profile at very short time-scales. This reveals a coupling between the periodic and the low-frequency aperiodic variabilities. In addition, near the end of the outburst a strong QPO feature centred at $\sim$0.135 Hz was detected. Using the QPO frequency and the X-ray luminosity during the QPO detection period, the magnetic field strength of the neutron star was estimated and found to be consistent with the value inferred earlier under the assumption of spin equilibrium.

Paul and Sachi Naik of PRL measured the timing and broad-band spectral properties of the Be transient high-mass X-ray binary pulsar GRO J1008-57 using a Suzaku observation in the declining phase of its November and December 2007 outbursts. Pulsations with a period of 93.737 s were clearly detected in the light curves of the pulsar up to the 80-100 keV energy band. The pulse profile was found to be strongly energy dependent, a double-peaked profile at soft X-ray energy bands ($<$8 keV) and a single-peaked smooth profile at hard X-rays. The broad-band energy spectrum of the pulsar, reported for the first instance from this work, is well described with three different continuum models, namely (i) a high energy cut-off power law, (ii) a Negative and Positive power law with EXponential (NPEX) cut-off and (iii) a partial covering power law with high energy cut-off. In spite of large value of absorption column density in the direction of the pulsar, a blackbody component of temperature $\sim$0.17 keV for the soft excess was required for the first two continuum models. A narrow iron Kα emission line was detected in the pulsar spectrum. The partial covering model, however, was found to explain the phase-averaged and phase-resolved spectra well. The dip-like feature in the pulse profile was explained by the presence of an additional absorption component with high column density and covering fraction at the same pulse phase.

A comprehensive spectral analysis of the high mass X-ray binary (HMXB) pulsar Centaurus X-3 was carried out using data obtained with the Suzaku observatory covering nearly one orbital period. The light curve showed the presence of extended dips which are rarely seen in HMXBs. During this observation, these dips were seen up to as high as $\sim$40 keV. The pulsar spectra during the eclipse, out-of-eclipse, and dips were found to be well described by a partial covering power-law model with high energy cut-off and three Gaussian functions for 6.4 keV, 6.7 keV, and 6.97 keV iron emission lines. The dips in the light curve were explained with the presence of an additional absorption component with high column density and covering fraction, the values of which were not significant during the rest of the orbital phases. The iron line parameters during the dips and eclipse were significantly different compared to those during the rest of the observation. During the dips, the iron line intensities were found to be lower by a factor of 2-3 with significant increase in the line equivalent widths. However, the continuum flux at the corresponding orbital phase was estimated to be lower by more than an order of magnitude. Similarities in the changes in the iron line flux and equivalent widths during the dips and eclipse segments suggests the dipping activity in Cen X-3 is caused by obscuration of the neutron star by dense matter, probably structures in the outer region

of the accretion disk, as in case of dipping low mass X-ray binaries. This study was done in collaboration with Sachi Naik from PRL.

Paul and Chetana Jain also studied the pulse profile stability of the Crab pulsar. An X-ray timing analysis of the Crab pulsar, PSR B0531+21, was carried out using archival RXTE data. The stability of the Crab pulse profile, in soft (2-20 keV) and hard (30-100 keV) X-ray energies, over the last decade of RXTE operation was investigated. The analysis included measurement of the separation between the two pulse peaks and intensity and the widths of the two peaks. No significant time dependency in the pulse shape was found. The two peaks were found to be stable in phase, intensity and widths, for the last ten years. The first pulse is relatively stronger at soft X-rays. The first pulse peak is narrower than the second peak, in both soft and hard X-ray energies. Both the peaks show a slow rise and a steeper fall. The ratio of the pulsed photons in the two peaks was also found to be constant in time.

Other research themes by Paul during the year gone by included studies of QPOs in the black hole transient XTE J1817-330; search for pulsations in the low mass X-ray binary EXO 0748-676; and variations in the X-ray eclipse transitions of Cen X-3.

S Sridhar's interests lie in the theoretical domain of galactic astrophysics. During the year, he continued his work on the physics of the dynamo action due to turbulence in shear flows.

He worked on a theory of the shear dynamo problem for small magnetic and fluid Reynolds numbers, but for arbitrary values of the shear parameter. Specializing to the case of a mean magnetic field that is slowly varying in time, explicit expressions for the transport coefficients were derived. He and JAP student Nishant K. Singh proved that when the velocity field is nonhelical, the transport coefficient vanishes. They then considered forced, stochastic dynamics for the incompressible velocity field at low Reynolds number. An exact, explicit solution for the velocity field was derived, and the velocity spectrum tensor was calculated in terms of the Galilean-invariant forcing statistics. Forcing statistics that are nonhelical, isotropic, and delta correlated in time were considered and specialized to the case when the mean field is a function only of the spatial coordinate and time. Explicit expressions were derived for all four components of the magnetic diffusivity tensor. These are used to prove that the shear-current effect cannot be responsible for dynamo action at small Re and Rm, but for all values of the shear parameter.

Sridhar and his collaborators from IUCAA, Kandaswamy Subramanian and Sanved Kolekar, addressed the shear dynamo problem in the context of "renovating flows". In such a flow, time is split into discrete and finite intervals and the random velocity fields in different intervals are independent and identically distributed. The advantage of this approach is that it allows the investigation of the shear dynamo problem for arbitrary values of the magnetic Reynolds number and shear strength.

Sridhar and Nishant Singh also derived exact solutions of the incompressible Navier-Stokes equations in a background linear shear flow. The method of construction is based on Kelvin's investigations into linearized disturbances in an unbounded Couette flow. Explicit formulae for all three components of a Kelvin mode in terms of elementary functions were obtained. It was then proved that Kelvin modes with parallel (though time-dependent) wave vectors can be superposed to construct the most general plane transverse shearing wave. An explicit solution was given, with specified initial orientation, profile and polarization structure, with either unbounded or shear-periodic boundary conditions. The manuscript for this work is nearing completion.

Radio galaxies have been the primary focus of **Lakshmi Saripalli**'s research work. During the year, her research themes included studying issues related to jet stability and origin of radio galaxy types from dust distributions in host elliptical galaxies. In collaboration with Ravi Subrahmanyan of RRI, Ron D. Ekers of CSIRO (Australia) and Elaine M. Sadler of the University of Sydney, Saripalli worked on the characterisation of radio galaxies in the sensitive, 1.4-GHz Australia Telescope Low-Brightness Survey (ATLBS). A sample of 119 extended radio sources (ATLBS-ESS) was compiled that yielded useful samples of high redshift, low power radio galaxies and radio sources with restarted nuclear activity. Using the ATLBS-ESS she also examined the potential for accessing the elusive, yet common, black hole growth and feedback processes. Using the same survey, she also looked at morphological classification of radio galaxies as a function of 1.4 GHz total power towards understanding the lifecycles of radio galaxies. This study was carried out with Kshitij Thorat of RRI.

Post-doctoral fellow **Siddharth Savyasachi Malu**'s research interests include galaxy clusters, particularly observations of the Sunyaev-Zeldovich effect (SZE) and radio halos, and Cosmic Microwave Background (CMB), which includes instrument optimization and analysis.

During the year, Malu completed the study of the SZE/Radio Halo in the Bullet cluster at 18 GHz from data collected in 2009. This study was in collaboration with Ravi Subrahmanyan, Mark Wieringa (Australia Telescope National Facility, CSIRO) and D Narasimha (TIFR). This study showed that the SZE has a compact feature and the radio halo and the SZE are co-spatial – both these features are unusual, and may be signatures of energetic mergers. To separate the radio halo and the SZE, more observations were done at 18 GHz and 22 GHz in the H168 and H75 arrays at the Australia Telescope Compact Array in July and September 2010. Malu and his collaborators are working on separating the two.

The MACSurvey recently discovered several hot ($T>8$ keV) and X-ray luminous clusters that exhibit disturbed X-ray morphologies. Given the connection between radio halos and cluster mergers, Malu, KS Dwarakanath and Ruta Kale looked into what percentage of X-ray selected massive clusters exhibited radio halos. They observed six different clusters using GMRT at 235 and 610 MHz and found that four of these clusters exhibited either a radio halo or a radio relic – diffuse emission associated with a merger. One cluster, MACS J0417, was of particular interest due to its unusually flat spectral index of -0.5 (radio halos have spectral indices in the range of -0.8 to -1.8 below 1 GHz). These findings were announced at the DRP conference in RRI in March 2011. Further analysis of the data is ongoing.

Another of Malu's research themes during the year was exploring the Fizeau beam combination for CMB interferometry, in collaboration with Peter Timbie of the University of Wisconsin-Madison. CMB observations have been very successful in providing stringent limits on cosmological parameters, and the next generation of CMB instruments aims to probe the Inflationary era through B-modes in CMB polarization. The usual approach in this regard is that of imaging the CMB through single dish instruments. However, the exquisite control of systematic effects required to reach the sensitivity to detect B-modes is not possible with single-dish instruments; hence the need to explore interferometry. At the same time, single-dish instruments are the ones that probe the correct angular resolutions required to characterize B-modes. This poses a problem. Fizeau beam combination offers a solution: it offers simultaneous recovery of an image as well as visibilities in the correct resolution range. A manuscript describing this technique has been prepared and will be submitted soon.

Cluster mergers exhibit not just radio halos, but diffuse emission far removed from cluster cores and radio relics, which are thought to be merger shocks. Malu, along with Joydeep Bagchi of IUCAA and Mark Wieringa of ATNF, studied the properties of these shocks so as to provide insight into the merger event and enable the modeling of the dynamics of merger events. Abell 3376 is a cluster merger that exhibits a double relic on either side of the shock. This double relic has previously been observed at 2 GHz using the VLA, but not at higher frequencies. Malu and his collaborators obtained data at 5.5 GHz and 9 GHz with ATCA in H214 and H75 arrays to study the behaviour of the spectral index of this double relic at higher frequencies. Analysis of data is ongoing.

During the last year, post doctoral fellow **Shashikant** worked on various problems in collaboration with Biswajit Paul, Biman Nath, Shiv Sethi and Tarun Deep Saini from IISc. Many of these studies are interconnected and required the analysis of X-ray and CMB data, computer simulations, and the use of statistical techniques.

He used RXTE slew data available in the public domain of RXTE to map the X-Ray sky. These maps will image the background sky in X-ray (2-60 keV). Although known point sources have been removed from the slew data, the group expects to detect new faint/variable sources. According to their estimates, with four seconds of observation at a point in the sky, they will have enough sensitivity to detect sources with milli crab intensity. RXTE slew data is available in two different categories – standard 1 and standard 2. The difference in the two categories is due to the different time binning and available spectral information. Standard 1 data is averaged and binned every 0.125 seconds, while standard 2 data is averaged and binned every 16 seconds. In terms of spectral difference, standard 1 has no spectral information, while in standard 2 has 129 spectral channels. Standard 1 data is used to map the sky, while standard 2 data is used to remove the instrument background.

Shashikant and his collaborators first extracted light curve – measure of the number of photons received by the detector with time – from the raw data. At the time, the satellite was slewing continuously and hence the photon count was collected at different positions in the sky. The next step is to find the position of the satellite with time. This information is provided in the filter file which is sometimes provided along with the observation. Photon count rate versus position maps have been generated around a few sources like PSR 1509-58. The above source was chosen as it was observed very frequently and thus has many slew observations around it in the public domain of RXTE. Computer programs have been written to perform the above task, which has been automated so that several data files can be handled simultaneously without human interference.

The source of X-ray background at E#8805; 1.0 keV is mostly extra-galactic, although at lower energies

E#8804; 1.0 keV most of the emission comes from the Milky Way itself. It is believed that Active Galactic Nuclei contribute to most of the high energy part of this background. The diffuse (without resolving the point sources) extra-galactic part of the X-ray background can trace the distribution of matter with a bias factor determined using the density traced by X-rays and the actual mean density of matter. The bias factor has been measured and is expected to be used in X-ray background maps to put constraints on the bias parameter. An extensive literature survey is going on along this line, though the calculation of the bias parameter requires some computation for which computer programs will be written.

Shashikant also worked on the detection of the integrated Sachs-Wolf effect. When the CMB photons pass through the matter distribution they can be blue/red-shifted due to the gravitational potential of the matter. While entering the matter they get blue-shifted and while leaving, they get red-shifted. This blue and red-shift would be the same if the gravitational potential of the matter does not change with time, which is the case in matter dominated cosmology. However, observations suggest that the expansion of the Universe has accelerated in the recent past (in terms of red-shift). This fact can be explained by assuming a component with negative pressure called dark energy. In case of a dark energy-dominated universe, the gravitational potential of the matter structures decreases with time. Thus the red-shift when the CMB photons leave the matter structure would be small compared to the blue shift when they entered it. This effect is known as late time Sachs-Wolf (SW) effect or Rees-Sciama (RS) effect. This net blue shift in the above SW or RS effect is correlated with the matter distribution and hence can be probed by looking for the correlation of the CMB anisotropies and the matter distribution.

This work produces the maps of X-ray background which can be used to probe matter distribution. For the CMB, sky maps from the WMAP experiment are going to be used.

In collaboration with Tarun Deep Saini of the Indian Institute of Science, Shashikant studied non-Gaussianity and direction dependent systematics in HST key project data.

Measuring an accurate value of the Hubble constant (HO) which requires an accurate measurement of distances, is one of the most challenging tasks in cosmology. Many times systematic errors dominate the accuracy of distance measurement and hence cause uncertainty in the measurement of HO. If the systematic effects depend on direction, they can cause a threat to the cosmological principle, which states that the Universe is isotropic and homogeneous at a given cosmic time. Apart from systematic errors, random errors are also a part of any experiment. Due to Central Limit Theorem we expect these random errors to follow a Gaussian distribution. This Gaussian noise can be used to infer parameters of interest from the observational data. If the random errors in the data are not Gaussian, the inference will be biased. Thus it is essential to know the nature of the errors in the data.

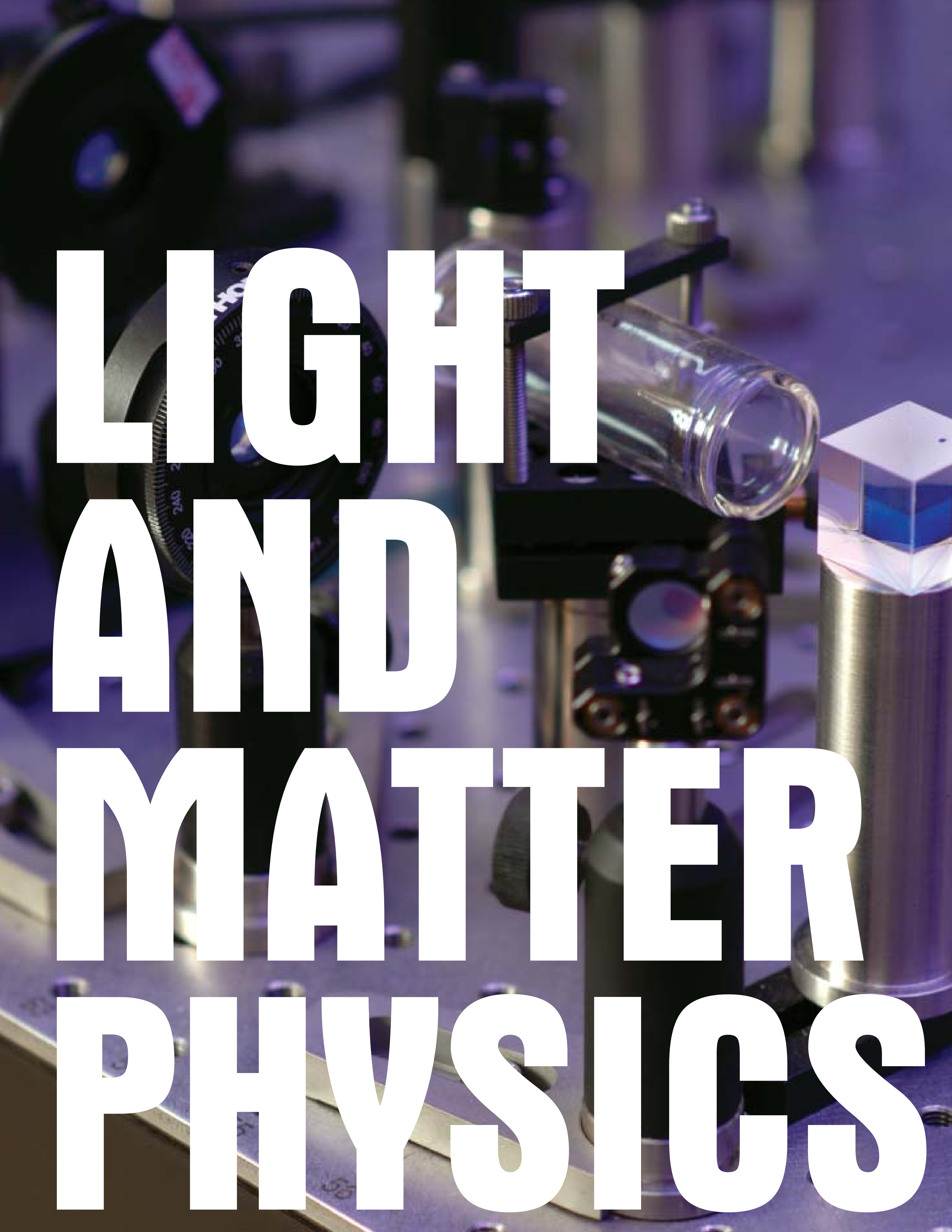
The direction dependent systematics and non-Gaussian features in the measurements of the Hubble constant provided by the Hubble Space Telescope (HST) were studied. Measuring HO with 10% accuracy was one of the "Key Projects" of the HST and it has provided the best measurement of the above so far. New statistical techniques have been derived based on extreme value theory to study the above features.

Research Associate **Harish Vedantham**'s work during the year included imaging with the MWA 32Tile system, in collaboration with N Udaya Shankar and Ravi Subrahmanyan of RRI, and studying the effect of astrophysical foregrounds and imaging algorithms on imaging the EOR. In this connection they have shown that using the windowing technique extensively used in spectroscopy can be very beneficial to the detection of EOR signal which reduces the contamination of the EOR signal by the foreground signals by several orders of magnitude.

They have also suggested usage of Chirp Z Transform (CZT) for imaging which decreases the stochastic noise in images generated using the conventional algorithms employing Fast Fourier techniques.

Research Associate **Mayuri S** worked with Ravi Subrahmanyan, N Udayashankar and Avinash Deshpande to explore different antenna designs for the Aperture Array so as to optimize performance while eliminating or minimizing setbacks faced in conventional structures. The design currently being investigated is a connected array structure capable of operating over a large bandwidth of 30 MHz to 860 MHz.

LIGHT AND MATTER PHYSICS



OVERVIEW

The Light and Matter Physics (LAMP) group, which was started in 1995, comprises of four motivated faculty members and their students. The members of the LAMP group combine knowledge from atomic, molecular, linear and nonlinear optical physics to study classical and quantum light-matter interactions. The group takes a holistic scientific approach, where the fields of theoretical, numerical and experimental research complement one another.

There are four labs that cater to the individual needs of the LAMP members:

– The Laser Cooling, Light Scattering Lab

– The Ultrafast and Nonlinear Optics Lab

– The Quantum Optics Lab

– The Quantum Interactions (QUAINT) Lab

The following pages summarize the major areas of research for the LAMP group. Each member's individual work during the last year is provided in the next section, giving the reader a more detailed and technical description of their respective research activities.

Quantum optics is a field in physics that applies quantum mechanics to study phenomena involving light and its interactions with matter. Since the first indication in 1899 that light may be quantized, the field of quantum optics has witnessed significant progress in our understanding of light-matter interactions and microscopic systems. Today's major fields of interest in quantum optics include the manipulation of elemental particles like atoms, ions and molecules and the use of quantum optics for quantum information.

LASER COOLING AND TRAPPING

Laser cooling and trapping is an area of physics that has largely expanded over the last decade. Presently, atoms can be cooled down to extremely low kinetic temperatures (as low as 1 microK) and trapped for a time period of the order of seconds. Such control over the motion of atoms allows researchers to probe their behaviour more precisely than before. There are a number of techniques to cool and trap atoms of alkali elements, with the most commonly used being the so-called Doppler cooling. It involves three mutually perpendicular laser beams that intersect at the centre of the chamber. A pair of magnetic coils produces a magnetic field that is zero at the centre of the chamber, and increases radially outward. Using appropriate wavelength and polarization of the laser beams, atoms can be cooled by repeated absorption and emission of light, and trapped by an inward force arising out of the combination of the polarized light beams and the spatially varying magnetic field. Such a system is called Magneto Optical Trap or MOT.

2D MOT: Researchers from the LAMP group are continuing their work on the construction of a 2 dimensional MOT. Currently, they are involved in the process of installing and testing of the coils that produce the magnetic force in the MOT.

MOT and Quantum Logic: As electronic devices become smaller and smaller, quantum effects like superposition and entanglement cannot be ignored and new ways of defining the basic states of 0 and 1 need to be found. To attempt quantum logical gates, the atoms need to be cooled and trapped in optical lattices such that the 0 and 1 states of a digital circuit can be mapped to internal states of the atom. The inducing of conditional transitions between these states is the equivalent of a logical gate. Currently, a MOT with the capability of trapping individual atoms is being built at RRI.

A Lattice of Ion Traps: Researchers at RRI had proposed a novel ion trap configuration that allows for high precision spectroscopy measurements, quantum information processing as well as new studies of few particle interaction systems. A scaled prototype of this trap has been built and tested with fluorescent particles in air. One or more charged particles can be loaded into the trap on demand and collective behaviour/interactions studied. Systematic measurements on trapped particles with this system are under way for an experimental understanding of the trap operation and following that a study of ion-ion interactions.

Atom Ion Molecule Experiment (AIM): Ions and atoms are trapped using different trapping principles. To manufacture a trapping scheme where both ions and atoms at very cold temperatures can be simultaneously trapped is a major conceptual and technical challenge. This very objective has been successfully attained by members of the LAMP group. Such an experiment allows for interactions between ions and atoms to be studied in great detail. Initial studies that relate to the thermodynamics of the ion-atom combined system are at an advanced stage. The enormous increase in the interactions within this dilute gas ensemble will be exploited in the near future for the synthesis of ultra cold molecules from ultra cold atoms.

LAMP

Molecule Ion Cavity Atom Experiment (MICA): To expand on the possibilities opened up by AIM, a new experiment has been designed and built in the past year. In addition to ion and atom traps, simultaneous and overlapped molecule and light traps have been created. The new features allow sensitive detection of the very feeble light from the trapped molecules. The cavity will permit light signal enhancement from atoms and molecules by a factor of several thousand. Once again very novel conceptual and engineering challenges were overcome to build the experiment. The experiment is now ready and initial experiments are detecting low light levels signals from atoms by the cavity.

Vapour Cell based Experiments: In order to understand the various aspects of light-atom, light-molecule interactions, several experiments have been performed on atoms and molecules in vapour cells. Questions such as how to switch the intensity of light in an atom-cavity system have been looked at in great detail. The spectroscopy of atoms and molecules in such cells was also undertaken. A very important class of measurement undertaken is related to the preservation of the atomic state of atoms under collisions. These experiments are done in special vapour cells where collision with the walls of the cell tends to preserve certain atomic states. It is therefore important to work on the reasons why state changing collisions are suppressed in these special coated cells. Work related to the material properties of these coatings was also undertaken.

ELECTROMAGNETICALLY INDUCED TRANSPARENCY (EIT)

EIT is a quantum mechanical phenomenon where, under specific conditions, an absorption line of a material can be cancelled changing it from opaque to transparent at that particular frequency. To observe EIT, two highly coherent lasers are tuned to interact with three or more quantum states of the material. Since 1990, considerable research activity has been devoted to the topic of EIT. RRI researchers are trying to build a strong fundamental understanding of this phenomenon using both theoretical and experimental methods.

QUANTUM WALK OF LIGHT

A random walk is a mathematical description of a trajectory where the successive steps are random. Classical random walks are used in search algorithms when the searched parameter space is random. They find application in the fields of computer science, physics, ecology, economics and psychology. Quantum walks are the equivalent of random walks in quantum computing and can form a part of a quantum algorithm. Members of this division are now investigating the quantum walk of light in the frequency space.

LIGHT PROPAGATION IN RANDOM MEDIA

Multiple scattering of light in random media, like fog, considerably reduces visibility. Researchers at RRI have developed a technique for imaging in turbid media, which is currently being tested for commercial applications like aircraft navigation.

The localisation of light in random media is a phenomenon that is not well understood. After extensive simulations, members of the LAMP group are now attempting to observe localisation of light experimentally using ferrofluids as a medium. Ferrofluids consist of a fluid (usually water) with ferromagnetic nanoparticles, that act like random scatterers, dispersed in it. The easy manipulation of the nanoparticles in ferrofluids allows the quick testing of various possible scenarios that lead to the localisation of light. The understanding of this phenomenon might open doors for future novel optical devices.

NONLINEAR OPTICS

When a dielectric material is irradiated with a high intensity laser beam, the polarization response no longer scales linearly with the intensity of the applied field. This results in interesting modifications of the refraction and absorption behaviour of the medium. Nonlinear optics is the branch of physics that investigates such nonlinear responses of materials to electromagnetic radiation. It is a broad field of research and technology, with device applications in telecommunications, optical storage and all-optical computing. Optical switches, saturable absorbers and optical limiters are just a few examples of devices utilizing the effects of nonlinear transmission. The LAMP group at RRI employs pulsed laser z-scan and degenerate four wave mixing (DFWM) to investigate the nonlinear optical properties of various types of materials, including nanoparticles and nanocomposites. To study the temporal evolution of the nonlinearity the group uses femtosecond pump-probe spectroscopy. Other supporting experimental techniques employed for these investigations are cw z-scan, absorption spectroscopy, photoluminescence and photoacoustics.

LASER INDUCED PLASMAS

Lightning is a beautiful (and often scary) example of how Nature can create plasma. Today, the technological evolution of lasers allows researchers to generate plasma routinely in their labs. Plasma (the fourth state of matter) can be generated from a solid, liquid or gas sample using high power pulsed lasers. Such plasmas are called laser induced plasmas and they find application in several technological fields. In material science Pulsed Laser Deposition (PLD) is a commonly used technique, where the laser induced plasma acts as the source of material to be coated on a suitable substrate for producing thin films and nanoparticles of various compositions. Laser Induced Breakdown Spectroscopy (LIBS), the optical emission spectroscopy of laser induced plasma, is a powerful technique that provides immediate elemental analysis of any material regardless of its physical state. LIBS is widely used for the detection of heavy metals in soil, aerosol characterisation, cultural heritage elemental analysis, process control in industry, and space exploration. Laser induced plasmas are also used in the field of medical diagnosis and surgery, laser ignition, propulsion and fusion.

Researchers from the LAMP group routinely conduct experiments to study the time evolution and spectral characteristics of plasmas generated by femtosecond and nanosecond lasers. At present metallic solids are being used as irradiation targets, and the experiments are performed in vacuum as well as under ambient pressure conditions.

LAMP

ONGOING RESEARCH

Andal Narayanan's research during the year included the study of the coherent Microwave Optical Double Resonance (MODR) phenomenon using a home-built microwave cavity and a dilute atomic vapour of rubidium atoms. In collaboration with her project assistant TM Preethi and M Manu Kumara and K Asha of Mysore University, Narayanan used the cylindrical microwave cavity at 3 GHz that was built and characterised during the last academic year. Narayanan's research using this cavity was to understand the nature of correlation transfer between two regimes of the electromagnetic spectrum. These correlations are generated initially between an atom and the microwave field. It is then transferred to between the same atoms and an optical field. The Electromagnetically Induced Transparency (EIT) effect was used to induce the interaction between the atoms and the microwave and optical fields.

The results of these experiments include the finding of quantum optical effects that depend on the relative phase between the microwave and optical fields. It was also found that these phase sensitive changes occur on a non-linear optical absorption phenomena. These findings could have potential use in making logical gates in the optical domain that are controlled by a phase change in the microwave domain.

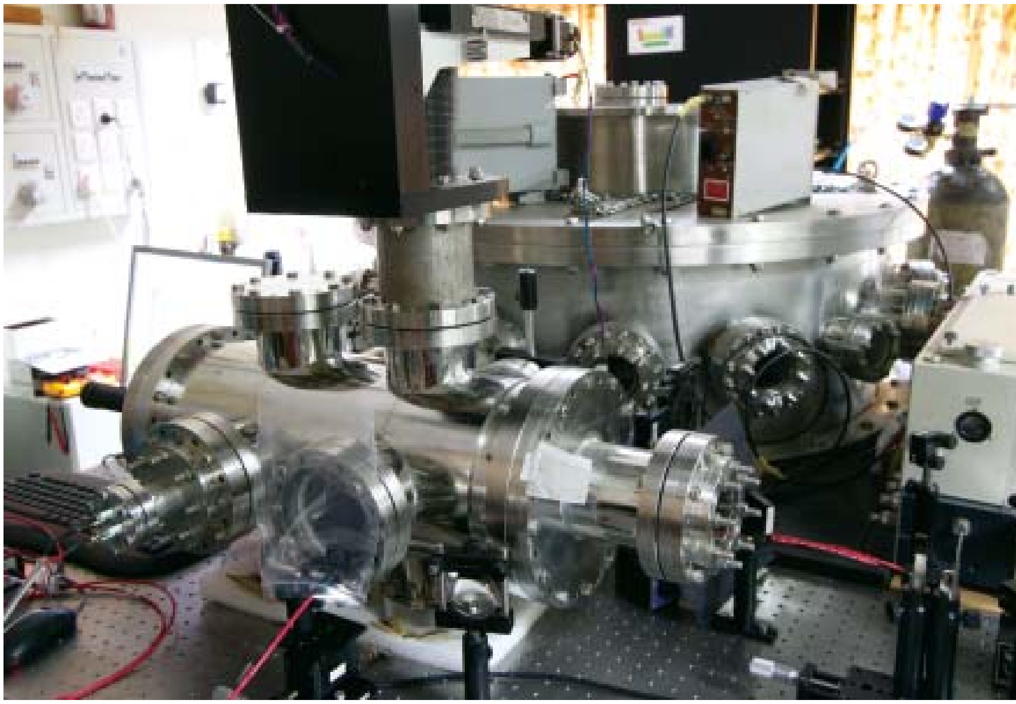
The cavity frequency was selected to match the ground hyperfine separation in the 5 S(1/2) manifold of 85Rb. This transition is a magnetic dipole transition and is traditionally used for Rubidium atom based clock frequency standard.

Other research carried out by Narayanan includes experiments with room temperature Rubidium atoms in a vapour cell, where results of interacting dark states in Rubidium 87 and Rubidium 85 were compared. An experimental signature is found to uniquely identify interacting superposition states of internal levels of Rubidium. The experimental signatures of two Rubidium isotopes were compared to identify the role of Doppler Effect. In Rubidium 87, where the level separation is larger than the Doppler width at room temperature, the interaction between the dark states occurs only at select detunings. Thus, in these systems, this effect serves as a directional frequency filter operating at optical frequencies. This research was carried out in collaboration with Preethi, researchers from Mysore University and P Sunil and Umakant Rapol from IISER in Pune.

Narayanan and J Vijay from BITS, Goa carried out dressed state and density matrix analysis for both N-level and tripod-level schemes in Rubidium when interacting with both microwave and optical fields. The N-level scheme's simulation agreed qualitatively with the experimental results. The results of the tripod-level scheme are currently being discussed with Jason Twamley of University of Macquarie, Sydney, and his colleagues.

Sadiq Rangwala's research interests span quantum interactions, ultra cold molecules, ion trapping and atoms and molecules in external fields.

In the previous year, Rangwala and his group had proposed a model for an ion trap that was three dimensionally symmetric. During the year gone by, he and his students constructed a working prototype of the model and conducted several tests on it, including trapping particles of fluorescent powders.



Research using the prototype is ongoing and will be largely driven by students. This prototype could be of tremendous significance in relation to harmonic oscillators.

The understanding of the ion atom experiment, which has several very original components, has been the primary focus of experiments during the year. Rangwala and his collaborators worked on the design considerations of an experimental apparatus and technique that simultaneously traps ions and cold atoms with spatial overlap. This apparatus can help study ion-atom processes at temperatures ranging from hot to ultra-cold – an area with respect to cold trapped atoms that has largely been unexplored. The ion trap and atom traps are characterized independently of each other. The simultaneous operation of both and the experimental signatures of the effect of the ions and cold-atoms on each other were studied. Studies are currently being conducted to address the issues of sympathetic cooling of ions by atoms and the possibilities of molecule formation, among others.

Over the last couple of years, Rangwala and his team have worked on putting together an experiment capable of trapping cold atoms, cold molecules, cold ions and photons. This experiment will allow them to laser cool Rb, K, Cs and Ca+ ion. These experiments will target the Fabry-Perot cavity based on the detection of trapped ultra-cold molecules. It is hoped that such an experiment allows the flexibility to perform a large class of experiments in Atomic, Molecular and Optical Physics. A prototype of this experimental design was constructed in January-March 2011 and its various key features, with the exception of the ion trapping part, have been successfully tested. It is believed from ongoing experimental results that the light emitted into the cavity mode is stimulated, but further studies are required to confirm this hypothesis. An important feature is that light from cold atoms is being dumped into the cavity, allowing the efficient measuring of the signal.

As part of his work in the area of anti-relaxation coatings for alkali metal vapour cells, Rangwala continued his research into paraffin coatings with positive and negative logic switching experiments with atoms in paraffin-coated cells. The main challenge with these experiments has been coupling light into the cavity mode when there is paraffin in the cavity mode. However, this study has the potential to help infer the role of stimulated emission in the system.

Measurements were also made to determine the density of rubidium dimer vapour in paraffin-coated cells. The number density of dimers and atoms in similar paraffin-coated and uncoated cells was measured by optical spectroscopy. Due to the relatively low melting point of paraffin, a limited temperature range of 43-80°C was explored, with the lower end corresponding to a dimer density of less than 107 cm^3. With a one-minute integration time, sensitivity to dimer number density of better than 106 cm^3 was achieved.

In addition to the cutting edge experimental programs in the QUAINT Lab, the lab also has a parallel programme of simulation of the experimental systems to gain an even better understanding of physics. Examples of such simulations include:

1. Ion traps and multiple ions in ion traps
2. Ion atom interaction (scattering) and the trapped ion trapped atom problem
3. Atoms in cavities
4. Molecular dynamics

Reji Philip's research interests cover laser-induced plasmas and optical nonlinearity of nanostructures. He continued his studies in LIBS (laser-induced breakdown spectroscopy) and temporal dynamics of the plasma plume, from the solid targets carbon, copper, aluminium, and zinc, kept at different vacuum pressures. Laser pulses of 8 ns width (at 532 nm and 1064 nm) were used for generating the plasma. A few measurements were conducted in nitrogen ambience as well. Philip is planning to repeat these measurements with ultrafast (100 fs) laser pulses, with which different dynamics are expected.

His research during the year also included optical nonlinearity studies in semiconductor quantum dots, ferromagnetic media, piezoelectrics and conjugated polymers. Philip and his collaborators determined the existence of surface states in doped ZnO nanostructures from an NLO measurement and observed broadband optical limiting in high surface area noble metal nanosponges.

Quantum computing is one of **Hema Ramachandran**'s research interests. She has conducted both theoretical and experimental work in the field of quantum walks. Her research on quantum logic is being pursued on two fronts – using light and atoms.

Building on her previous work, which demonstrated a four-step quantum walk of light, during the past year she and her students succeeded in imparting controlled phase shifts to the walker (light) through an acousto-optic interaction. This electronically controlled implementation permits rapid and precise control, and can be adapted to single-photon walks with little effort.

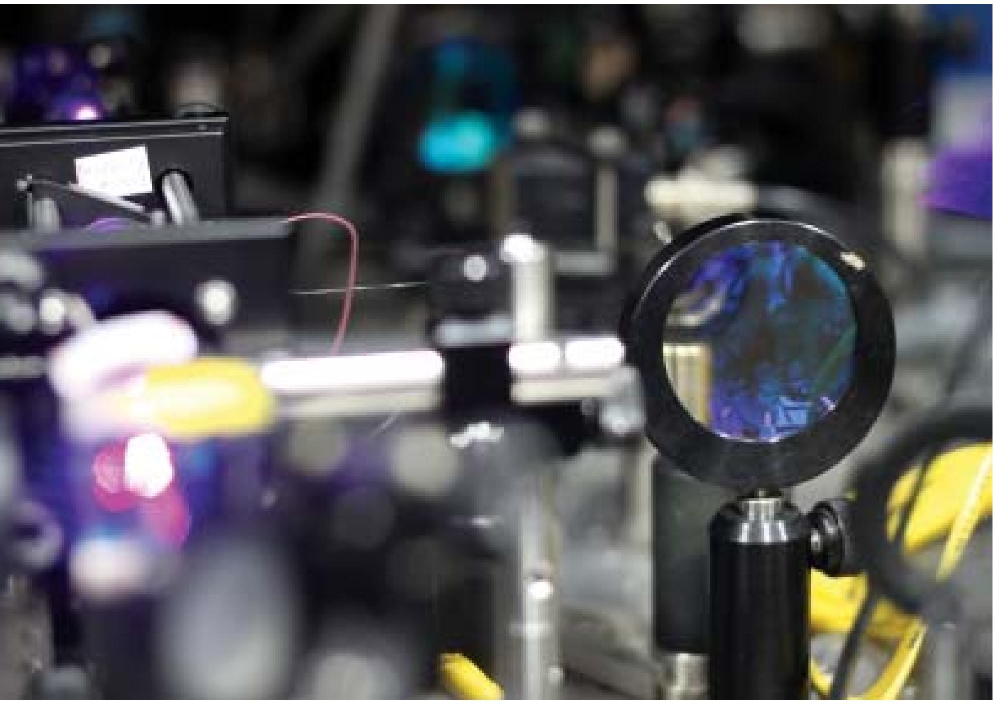
She and her students are also investigating the use of atoms for quantum logic, where atoms, in superpositions of different electronic states, form the qubits, and their controlled transition is brought about by light. Towards this, they devised a scheme using the 5S1/2, 5P3/2 and 5D5/2 levels of Rb. Exciting the 5D5/2 level required and tuning lasers appropriate for this have been completed, and the hyperfine structure of 5D5/2 level has been mapped. They are now attempting a C-NOT operation using a cascaded scheme. Once a C-NOT operation has been demonstrated using atomic vapours, the same will be demonstrated using single atoms. For this, a single-atom trap is being built. The design of the vacuum chamber and the lens holder has been optimized, and these have been built and tested.

Another of Ramachandran's research themes was light in random media. Light propagation through two kinds of random media formed the subject of her research. The first is fog, and the aim has been to image through it. The second material is a ferrofluid, which is a random suspension, in liquid, of nanospheres that are magnetic. The application of an external magnetic field alters the arrangement of the nanospheres, leading to interesting optical characteristics.

During the previous year, Ramachandran and her team had planned an experiment for imaging through turbid media, with the specific application of using the technique for navigation. A proof-of-principle experiment envisaged placing a polarized light source on top of a high tower (a TV tower in Rennes, France), and imaging this light source through fog using polarization discrimination in a nearby laboratory. Preliminary work has been carried out. A source, with the requisite characteristics (wavelength, intensity, polarisability, continuous outdoor operation) was tested atop the TV tower; it has been functioning for several months, in all types of weather. Data collected at the lab has to be analysed. This study was done in collaboration with Mehdi Alouini and Julien Fade of University of Rennes and Fabien Bretenaker of University of Paris.

The work on the unusual transmission and reflection of light by ferrofluids was continued. On the experimental front, a large parameter space was investigated in a systematic manner, and at different wavelengths of light, with the experiment being automated so as to obtain millisecond timing accuracy. On the theoretical front, analytical expressions for optical parameters were derived and the possibility of coherent Dicke scattering examined. Inferences from these studies include the belief that ferrofluid is a novel medium, where one can impose weak spatial order, that may be tuned, by means of an externally applied magnetic field. This, along with the weak dissipation that is present in the medium, would provide a "Lossy Anderson-Bragg" (LAB) cavity where the interplay of random multiple scattering, Bragg scattering and loss would lead to unusual effects, like the simultaneous decrease in transmission and reflection of light.

Numerical simulations were then performed, where, using the method of invariant imbedding, the transmission and reflection coefficients were calculated as a function of the wavevector for a range of disorder and loss.



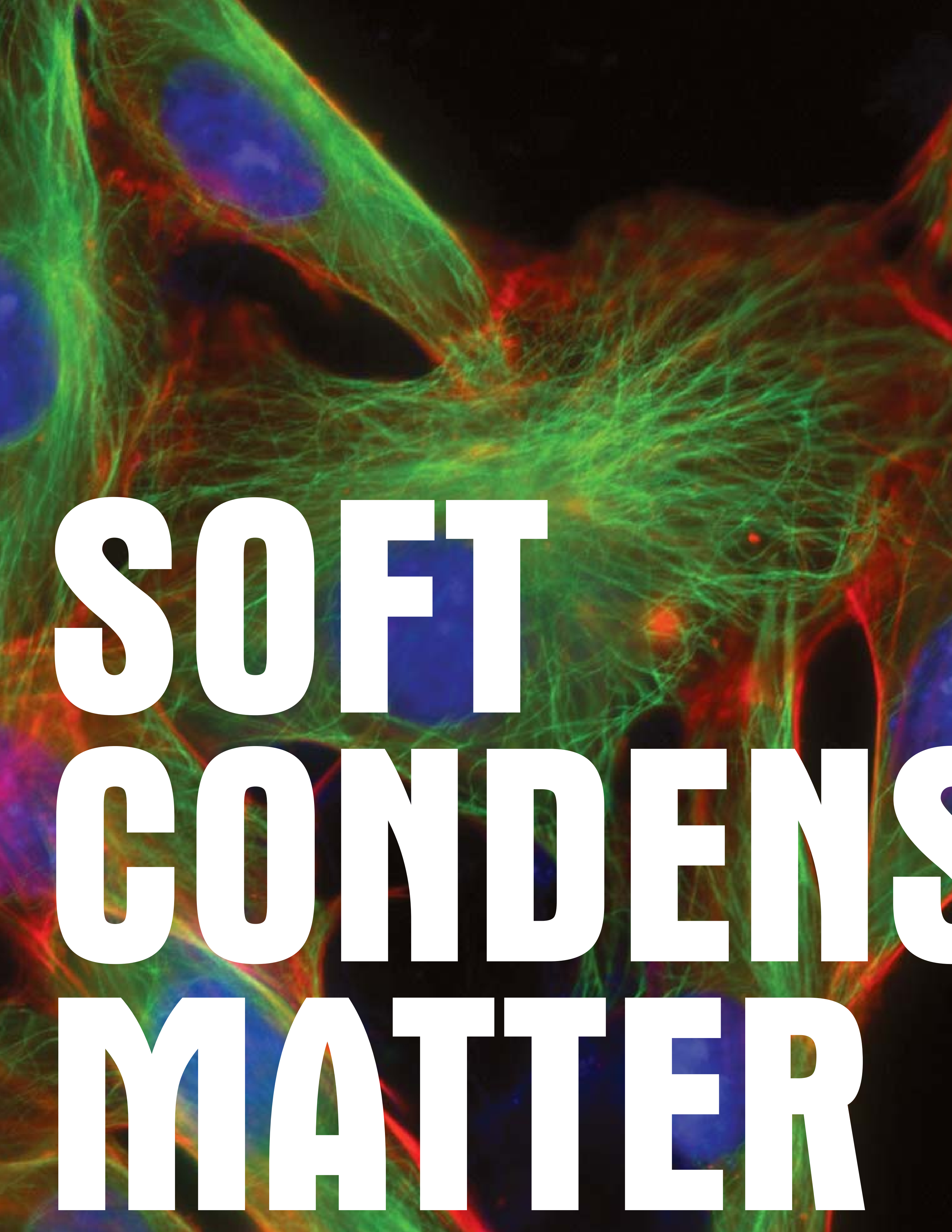
At the Bragg condition, a simultaneous dip in the transmission and reflection was observed, confirming the picture of the LAB-cavity. This work was carried out in collaboration with M. Shalini of Mumbai University, D. Mathur of TIFR, Divya Sharma of BITS Pilani (at Hyderabad), and AA Deshpande and N Kumar of RRI.

Building on recent work on light emission by carbon nanotubes (CNTs), Ramachandran and her collaborators noticed the formation of bubbles in the surrounding fluid, which then could be trapped at the tweezer focus. This bubble formation was attributed to the photo-thermal heating of the CNTs and its vicinity, leading to the expulsion of hot gas from within the CNTs and vaporisation of the immediate surrounding fluid. They studied the dynamics of these bubbles (in experiments carried out at TIFR, Mumbai), and have distinguished between gaseous and vaporous bubbles. Numerically solving the hydrodynamic equations, the mechanism of the formation of bubbles of either kind has been elucidated, and has shown how extremely high temperatures may be reached. This confirms their earlier surmise of hot-spots in the context of white light generation from CNTs.

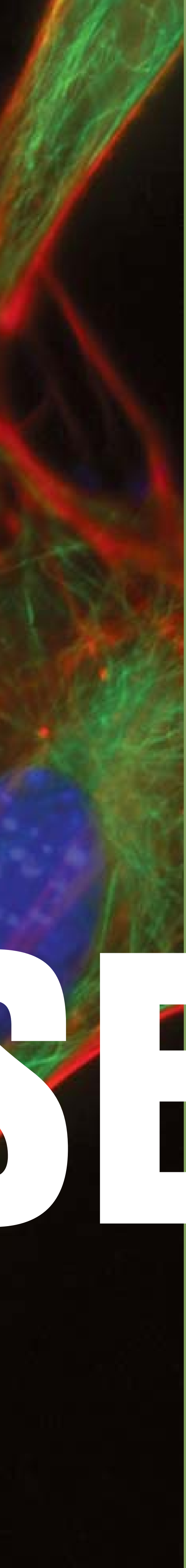
Collaborators for this study, which has now been published, included Deepak Mathur of TIFR and his team and Aniruddh Pandit of UDCT.

Post Doctoral Fellow **J Solomon Ivan**'s field of interest is the quantum information theory. During the year, his work on Bosonic Gaussian channels was completed and a detailed analysis on the operator sum representation of single-mode Gaussian channels appeared in the arXive. Ivan worked with Krishnakumar Sabapathy and R Simon of the Institute of Mathematical Sciences (IMSc), Chennai. Research into the relationship between nonclassicality and entanglement in the non-Gaussian context was also completed in collaboration with several researchers across the globe.

Other areas of study for Ivan included studying the robustness of non-Gaussian entanglement. The results of this study indicate that non-Gaussian entanglement is more robust against Gaussian noise and refute the conclusions of Allegra et al. This work was also done in collaboration with Sabapathy and Simon of IMSc.



SOFT CONDENS MATTER



SED

OVERVIEW

The Soft Condensed Matter (SCM) group, formerly known as the Liquid Crystals group, concentrates its research activities in the area of liquid crystal synthesis, characterisation and other analysis of their physical properties. The group recently expanded its activities to investigate other soft condensed matter like polymers, colloids, amphiphilic systems and nanocomposites. Theoretical and experimental research today includes the well established area of liquid crystal synthesis and characterisation as well as electrochemistry and surface science, liquid crystal displays, rheological studies of soft condensed matter and biophysics. The research environment of the SCM group is highly interactive with constant knowledge sharing and exchange of ideas among chemists, electrochemists, condensed matter physicists, theoretical physicists and members with statistical physics expertise.

The following pages summarize the major areas of research for the SCM group. Each member's individual work during the last year is provided in the next section, giving the reader more detailed and technical description of their respective research activities.

LIQUID CRYSTAL SYNTHESIS

A liquid crystal (LC) is a liquid whose molecules are regularly arranged in one or two dimensions such that it exhibits some optical properties associated with crystals. LCs exist in the so-called mesomorphic state, or a state of matter between liquid and solid. A mesogen is the fundamental unit (or molecule) of a LC that is responsible for the structural order observed in these substances. Typically, LC molecules consist of a rigid and flexible part. The first one gives rise to the crystalline properties, while the second causes the fluidity.

There are several varieties of liquid crystals. The important classifications are based on the shape of the molecules, their orientation, and nature of the material. Nematic LCs have their molecules arranged in loose parallel lines, while Smectic LCs have molecules that are aligned in a series of layers, with the axes of the molecules perpendicular to the plane of the layers. Calamitic LCs have the so called rod-like mesogens while discotic LCs have disk-like mesogens. There are also a class of LCs synthesised with bent-core or banana shaped mesogens. Thermotropic LCs exhibit phase transition into LC as temperature changes. Lyotropic LCs phase transition is a function of both temperature and mesogen concentration in a solvent.

LCs are primarily known for their extensive exploitation in electro-optical display devices such as watches, calculators, telephones, personal organisers, laptop computers and flat panel televisions. They also have diverse applications in chromatography, spectroscopy, holography, temperature sensing, as solvents in chemical reactions and more.

The Organic Chemistry Lab at RRI is involved in the synthesis and characterisation of a wide range of liquid crystals. More than 700 compounds with bent-core or banana-shaped molecules have been synthesised and characterised with some of them exhibiting novel mesophases (the phase between crystalline and isotropic liquid) and interesting properties like spontaneous electrical polarisation. The lab is equally active in the synthesis of novel disc-like mesogens that have important electronic and optoelectronic properties. Collaborating with other members of the SCM group, the Organic Chemistry Lab often synthesises compounds that exhibit specific physical properties like ferroelectric, antiferroelectric or columnar phase as well as oligomeric and polymer mesogens or compounds with novel metallo-mesogens with magnetic properties. The lab is equipped with polarising microscope, differential scanning calorimeter, digital micropolarimeter, infrared spectrophotometer, UV-Visible spectroscopy, elemental analyser, in addition to basic equipments required for chemical synthesis.

PHYSICAL MEASUREMENTS

Members of the SCM group at RRI investigate phase transitions, structure, molecular organization and physical properties of thermotropic liquid crystals with rod-like, disc-like and bent-core banana shaped molecules. The magnetic properties of liquid crystals and their nanocomposites are also currently being studied. Nanocomposites (nanoparticles – liquid crystal composites) is an active area of research for RRI. Dispersion of metallic, magnetic or ferroelectric

nanoparticles in different liquid crystals are very promising for novel future device applications. One of the major challenges in the field right now is the understanding of the mechanisms of self assembly of nanoparticles so that reliable control of the dispersion can be achieved with sufficient repeatability for high technology applications. The main advantage of LCs is their responsiveness to external stimuli like electric and magnetic field which provides more control on the dispersion process and tunability of the nanocomposites. Currently, the SCM group is working with $BaTiO_3$, gold nanoparticles and carbon nanotubes.

Often, novel measurement techniques are developed and used to measure the responses in varieties of liquid crystals with higher precision and accuracy. Typical measurement techniques involve dielectric spectroscopy, optical birefringence, polarizing optical microscopy and others.

LIQUID CRYSTAL DISPLAYS (LCDs)

LCD technology is the most common and widespread display technology in the world today. LCDs are literally everywhere, in our cell phones, televisions, laptop computers, video players, digital watches, calculators, gaming devices! They are much thinner, lighter, portable, more reliable and draw much less power compared to the old display techniques. Research activities at RRI focus on the development of new addressing techniques of the drive electronics in LCDs with passive matrix that would further reduce power dissipation and hardware complexity. RRI has applied for 16 US and European patents related to its research activities. Today, a multiline addressing technique, invented here, is extensively used in LCD electronics worldwide. The LCD lab has basic facilities to fabricate LC cells and small size prototype displays for testing purposes.

RHEOLOGY AND LIGHT SCATTERING STUDIES

Rheology studies the deformation and flow of matter when different kinds of stress are applied to the sample. Rheology builds on top of the classical elasticity and Newtonian fluid mechanics to extend our understanding to materials whose mechanical behaviour cannot be described with these classical theories. It is used to make predictions for the mechanical behaviour of a material based on its microscopic structure. Rheology has important applications in engineering (development and use of polymer materials), geophysics (studies of mud, snow, magma, etc) and physiology (blood flow measurements).

Researchers at RRI use rheology and light scattering techniques to study the dynamics and various responses in soft glassy materials. Examples of these are various concentrated suspensions, emulsions and gels used widely in industry. Soft glassy materials exhibit slow dynamics and serve as excellent model systems in the understanding of non-equilibrium glass transitions in hard condensed matter. A mix of synthetic clay suspended in water called Laponite is currently the material of choice for the group's research. The same material is used to study instabilities at the interface that occur when a low viscosity fluid (water) is injected into a more viscous one (aging clay suspension). Such studies are important for various technological processes like percolation of oil through porous rocks.

Amphiphilic compounds consist of molecules that have both hydrophobic and hydrophilic parts. At high enough concentrations the amphiphilic molecules start to form micelles or vesicles (amphiphilic molecules group together in various 3D structures arranged with their hydrophilic part facing the solvent). Amphiphilic block copolymers are a type of copolymer that is used in pharmaceutical applications for sustained-release technologies or gene delivery. Because of their amphiphilic nature when suspended in aqueous solution they start to form micelles. The hydrophobic core of the micelles serves as a reservoir for hydrophobic drugs. Pluronic triblock copolymer is a type of amphiphilic copolymer that is extensively studied by researchers at RRI because of its enormous potential for controlled drug delivery applications. Rheology techniques are utilised to study its stability under stress and strain, and determine the temperature-concentration phase diagram. Dynamic light scatterometry techniques are used to extract the size distribution in the sample.

ELECTROCHEMISTRY AND SURFACE SCIENCE

The Electrochemistry and Surface Science lab at RRI is actively involved in various research activities related to:

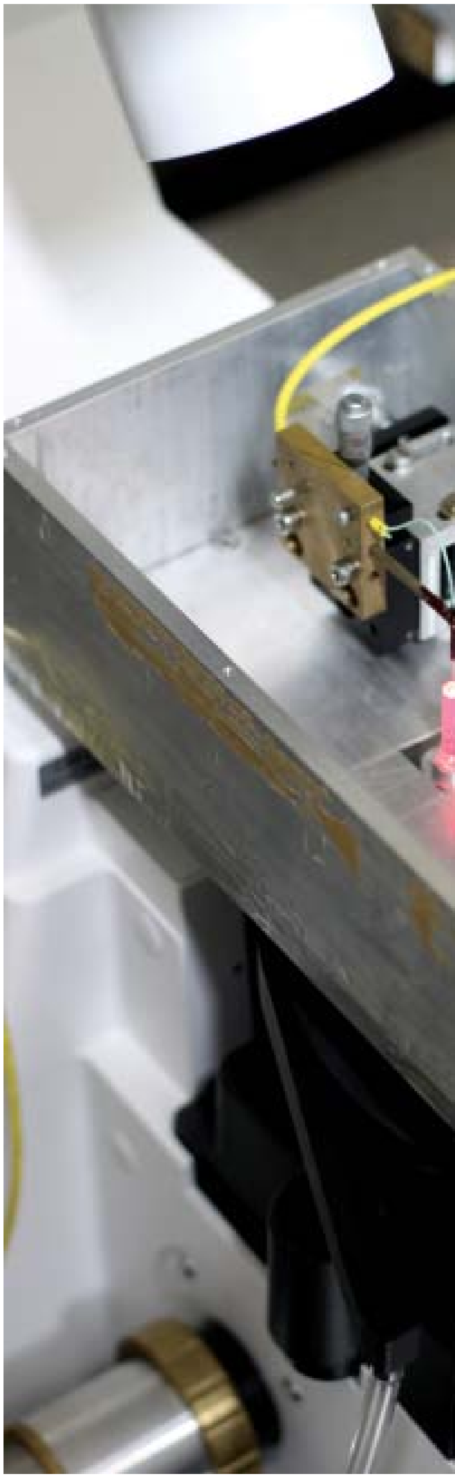
(i) electron transfer processes of redox molecules;

(ii) electrical and photoconductivity of doped columnar discotic liquid crystals;

(iii) electrochemistry of surfaces and interfaces formed by self-assembled monolayers and other organic thin films;

(iv) electron transfer processes and conductivity in bio-molecules on electrode surfaces;

(v) characterisation of conducting polymer nanostructures. The latter can lead to potential applications in sensors, energy conversion devices and fuel cells. The lab is equipped with modern facilities allowing for a wide range of measurement techniques to be applied. Some of the extensively used equipment include atomic force microscope, scanning tunnelling microscope, electrochemical quartz crystal microbalance, frequency response analyser and many more.



BIOPHYSICS

The Biophysics lab is part of the SCM group that was started just two years ago. Today, it is a self-sufficient lab where cells can be grown, manipulated and analyzed. The primary research focus in the Biophysics lab is the understanding of cellular

dynamics like force generation, movement and transport processes. A variety of cells is grown in the lab and tested using novel experimental techniques. Axons are a part of the neuron that extends from the neuron's cell body. In the majority of cases, axons are found to transmit electrical pulses. They are effectively the transmission lines of the nerve system. Members of the Biophysics lab are currently involved in the design, construction and integration of an experimental set up that can provide insight into the deformations and dynamics in axons. Experimental research of the patterning and differentiation of stem cells is another important activity of the lab.

PHASE BEHAVIOUR OF SURFACTANTS

Surfactants are amphiphilic organic compounds that allow easier spreading between two liquids or a liquid and solid. They are widely used in our everyday life as detergents, foaming agents and emulsifiers. The research endeavour of the SCM group is focused on fundamental understanding of the phase behaviour of various surfactants with equal emphasis on interpretation of experimental results and development of analytical models.

Lipids are a group of molecules that form an important structural component of cell membranes. Their main biological function includes energy storage and "signalling". A lipid bilayer is made up of two layers of lipid molecules to form a continuous barrier around the cell called membrane. The cell membranes of almost all living organisms and many viruses are made of lipid bilayers. Recently, a phenomenological theory of phase transition in lipid bilayers has been formulated by researchers at RRI. A study of the structural changes induced in lipid bilayers bound to toxins and the development of a new technique to extract their electron density profiles is underway.

LIQUID CRYSTALS THEORY

Theoretical work is conducted by many of the SCM group members parallel to their experimental projects. Analytical models are being developed for the behaviour of various liquid crystals, membranes and polymers.

ONGOING RESEARCH

Sandeep Kumar's research interests include the design, synthesis and applications of various liquid crystalline materials and the structure-property relationship in these self-assembling supra-molecular architectures. During the year, he furthered his work in the synthesis, characterisation and understanding of several new mesogens through individual and collaborative research.

His work included the study of discotic liquid crystalline gemini ampiphiles. The chemical structures of these salts were examined by 1H NMR, IR, UV, MS, and elemental analyses. The mesomorphic properties of these discotic dimeric salts were investigated by polarizing optical microscopy, differential scanning calorimetry, and X-ray diffraction studies. These gemini dimers with bromide as a counter ion were found to exhibit liquid crystalline behaviour over a wide temperature range and display ionic conductivity in the range of 10-6 to 10-5 S/m. It was found that these materials tend to form monolayer at the air-water interface.

The incorporation of photorefractive molecular units, such as carbazole, into anisotropic materials (liquid crystals) may offer many advantages over conventional electrical poling of photorefractive polymers. Keeping this in mind, Kumar and his collaborators (M Manickam, P Iqbal, N Spencer, PR Ashton, KJ Donovan and JA Preece) synthesised and characterised a series of symmetric 3,6 disubstituted carbazole derivatives with well-known biphenyl and triphenylene liquid crystalline moieties. Though the pure compounds are not liquid-crystalline, they may be of interest in the field of photorefractivity.

In collaboration with KA Suresh and group from RRI, physical studies on liquid crystalline materials were conducted. One of these studies included that of the Langmuir monolayer of a novel molecule containing a dimer of disk shaped moiety at air-water interface. The monolayer exhibited the coexistence of condensed and gas phases at a large area per molecule, which on compression transformed to a uniform condensed phase at lower area per molecule and collapsed at an even lower area.

The monolayer film transferred by the Langmuir-Blodgett technique onto a hydrophilic silicon substrate was studied using an atomic force microscope. These studies showed that the collapse pressure increased with an increase in the compression rate. Studies on the effect of temperature on the collapse pressure of the triphenylene-dimer monolayer showed that the collapse pressure decreased with increase in temperature. The analysis of the relative area loss as a function of time in the collapse region suggested that the monolayer collapses by the formation of nuclei of three-dimensional crystallites.

Arun Roy is part of the Soft Condensed Matter group and his research interests include phase transitions and electro-optic properties of liquid crystals and the physics of nanomaterials and nanocomposites.

One of his research themes during the year was the study of the blue phase LCD. The electro-optic effect with blue phase has several advantages: It has sub-millisecond response to an electric field; unlike the conventional LCD, response times are independent of thickness of the display cell; and it does not demand the alignment of liquid crystal molecules at the inner surfaces of the cell. The quick response of blue phase LCD can help simplify the circuit necessary to drive the display. However, the high and narrow temperature range of blue phase poses a challenge with regard to its use in practical devices. Roy, in collaboration with Sandeep Kumar and TN Ruckmongathan, is looking at fabricating a blue phase LCD cell based on literature survey to gain insight on the working of the cell.

Roy conducted experimental and theoretical studies into randomly polarised smectic A phase exhibited by bent-core molecules. He and his collaborators reported experimental studies on a newly synthesised bent-core liquid crystal exhibiting partial bilayer $SmAdP_R$ and $SmAdP_A$ phases. Though the $SmAdP_R$ phase appears to be optically uniaxial, as that of the Smectic A phase, the following distinctive properties of the former were observed:

- A current peak associated with a polarisation reorientation process under the application of a triangular wave voltage
- Large variation of the effective birefringence of the planarly oriented sample with the applied in-plane electric field
- The presence of a strong dielectric mode

A simple theoretical model was developed to describe the properties of the $SmAP_R$ phase and the transition from the $SmAP_R$ to the $SmAP_A$ phase. It was proposed that the above characteristic properties of the $SmAP_R$ phase arise due to the strong coupling between the transverse polarisation and the transverse polar order of the bend directions of the bent-core molecules in the layers.

Roy worked on this along with BK Sadashiva, postdoc fellows Meenal Gupta and Soma Datta and S Radhika.

Using a new electro-optic technique, Roy and Datta investigated the critical behaviour of the electroclinic response in the chiral Smectic A* phase in the vicinity of the transition from the Smectic A* to Smectic C* phase. The technique took into account the nonlinearity of the electroclinic response close to the transition temperature and allowed for the measurement of the electroclinic coefficient, relaxation frequency and the nonlinear coefficient of the electroclinic response. The electroclinic coefficient diverges with decreasing temperature as the transition temperature is approached. The measured critical exponent agrees well with the predictions of mean field Landau theory, though the measured nonlinear coefficient was found to be temperature dependent contrary to the usual assumptions of the mean field Landau theory.

Roy's research also included studying the physical properties of various liquid crystal compounds. The colloidal dispersions of nanoparticles in liquid crystals were investigated experimentally using the thermotropic liquid crystalline compound 4-n-octyloxy 4-cyanobiphenyl (8OCB) doped with $BaTiO_3$ nanoparticles. It was found that the physical properties of these dispersions vary considerably depending on the method of preparation of the dispersions. It was also found that aging the sample improved dispersal of the nanoparticles in the host liquid crystal, and hence enhanced the stability of the dispersions. This study was in collaboration with R Pratibha, Meenal Gupta and Ipsita Satpathy.

Roy and Gupta, in tandem with Veena Prasad and NG Nagaveni from the Centre for Liquid Crystal Research, synthesized and reported the mesomorphic properties of five new series of azo fuctionalised phasmid-like compounds formed by covalent bonding. The compounds comprised both symmetric and non-symmetric molecules, and most were found to be liquid crystalline with unusual behaviour. They exhibited mainly nematic, columnar and smectic mesophases. In a few cases, higher order mesophases were also observed. These mesophases were studied using polarizing optical microscopy (POM), differential scanning calorimetry (DSC) and X-ray diffraction (XRD). Based on the results, the team proposed a model for the molecular arrangement in the columnar phase as a centre rectangular.

Roy and his collaborators, R Pratibha, S Radhika, Meenal Gupta and BK Sadashiva from RRI, investigated the phase behaviour and physical properties of a new homologous series of compounds consisting of hockey-stick shaped molecules synthesised in RRI's chemistry laboratory. To characterize the different phases, various experimental studies were conducted on these compounds, including optical observations on confined samples and freestanding films; miscibility studies; X-ray diffraction studies; and dielectric spectroscopy. These studies showed that the compounds exhibited unusual tilted lamellar phases. The results will be included in the manuscript currently under preparation.

TN Ruckmongathan runs the Liquid Crystal Display Lab where his group is focused on the development of new addressing techniques to drive liquid crystal displays. Reduce power dissipation and hardware complexities of drive electronic in LCDs are some of the goals of his research work. He is also collaborating with Sandeep Kumar and Arun Roy, to study blue phases in liquid crystals with an ultimate goal of fabricating a blue phase LCD cell.

Building on his recent work on cross- pairing of select and data voltages to generate thousands of RMS voltages with just a few voltages in a line-by-line addressing technique; Ruckmongathan is exploring the possibility of doing the same when the display is driven by selecting multiple address lines. The hardware complexity of data drivers that are used to drive a matrix display increases with the number of grey shades. The aim of this research is to reduce the hardware complexity of data drivers in RMS responding LCDs.

In addition to these topics, Ruckmongathan is continuing his work on finding a simple and elegant method for 2-D addressing of matrix displays.

R Pratibha's research interests lie in the fields of liquid crystals and nanocomposites.

Bent-core mesogens have the ability to combine polar order and chirality and form several novel phase structures that are of considerable interest. Further, variation of the bent molecular architecture from a symmetric to an asymmetric one, can give rise to very different physical properties. Pratibha, along with Meenal Gupta and Arun Roy has carried out detailed experimental studies on a new series of compounds made of asymmetric bent-core molecules recently synthesised by S Radhika and B K Sadashiva. Based on optical observations on both confined samples and freestanding films, miscibility studies, X-ray diffraction studies and dielectric spectroscopy, they have shown that a lamellar phase exhibited by these compounds has a new and thus far unreported type of smectic structure.

Another one of Pratibha's research topics during the year was related with liquid crystal – gold nanoparticle composites. The surface plasmon resonance of metal nanoparticles is known to be very sensitive to the size and shape of the particles and the surrounding dielectric environment. Her earlier studies using gold nano spheres had shown that the surface plasmon resonance wavelength can be tuned as a function of the concentration of the particles in the liquid crystal matrix. Pratibha and Uma Maheswari have now extended this study using nanoparticles with elongated and anisotropic shapes which have the added advantage that their aspect ratio can be used as an additional tunable parameter for practical applications. The work involved the synthesis and characterisation of the gold nanoparticles using optical absorption spectroscopy and TEM. Detailed optical and dielectric measurements have also been carried out on these composites.

Liquid crystals made of bent-core molecules can exhibit polar ordered smectic phases that are ferroelectric or antiferroelectric in nature and exhibit electrooptic switching behaviour. However, transitions between such switchable phases, is not common. To understand the molecular origin of the dielectric relaxation processes, Pratibha and Archana Amatya have carried out dielectric studies on a bent-core liquid crystal exhibiting a transition between two such switchable phases.

Ranjini Bandyopadhyay runs the Rheology and Light Scattering Lab. Her research group employs dynamic light scattering, rheology, optical imaging or a combination of these techniques to study the structures, dynamics, stability and mechanical responses of a diverse range of soft materials.

Her research on the jamming transition in triblock copolymer solutions and in triblock copolymer-anionic surfactant mixtures included conducting photon correlation spectroscopy and rheological measurements to study the microscopic dynamics and mechanical responses of the solutions and mixtures. Increasing the concentration of triblock copolymers in an aqueous solution results in a sharp increase in the sample viscosity. This is understood in terms of the changes in the aggregation and packing behaviours of the copolymers and the constraints imposed upon their dynamics due to increased close packing. Adding suitable quantities of an anionic surfactant to highly viscous copolymer solutions results in a decrease in the sample viscosity by several decades. This indicates that the shape anisotropy and size polydispersity of the micelles comprising mixtures cause dramatic changes in the packing behaviour, resulting in sample unjamming and the observed decrease in viscosity. Bandyopadhyay and her collaborator Rajib Basak plan to use this research to study the potential of Pluronic as a drug delivery agent.

The glassy phase is an out-of-equilibrium, disordered state of matter that originates due to the jamming of the constituents of the system. In this jammed or frozen state, the motion of the constituents appears to be arrested and the dynamics of the system continues to slow down with time – a phenomenon known as aging. Colloidal glasses are soft glasses (i.e. they have a very low shear modulus when compared to hard glasses) that exhibit all the properties typically expected in hard glassy materials. This research targeted various issues regarding glass formation in the context of colloidal suspensions prepared by dissolving a glass former (Laponite – a synthetic hectorite clay) in highly deionized water. In colloidal glasses, the constituent particles or clusters are trapped in cages formed by their neighbours, which restricts their motion and slows down their dynamics. These caging dynamics were studied through Dynamic Light Scattering (DLS) experiments.

When a low viscosity fluid is injected into a more viscous fluid, a fingering instability called the Saffmann Taylor instability results. The understanding of this instability and the resulting finger patterns are important due to the ubiquity of such processes in technological applications, such as in the percolation of oil in porous rocks. The main purpose of this project is to investigate the physics behind the pattern formation at the quasi-two dimensional interface between a Newtonian fluid (water) and an aging non-Newtonian fluid (an aqueous suspension of the synthetic clay, Laponite). It was found that the fractal dimensions of the patterns change significantly as the age of the Laponite suspension changes. This research was done in collaboration with Debasish Saha and Pawan Nandakishore from RRI and Rama Govindarajan from JNCASR.

Cornstarch suspensions consist of irregular disk-shaped particles of average size 14 microns. Above a concentration-dependent critical shear rate, cornstarch suspensions shear thicken. It is widely believed that at even higher shears, cornstarch suspensions form nonequilibrium shear bands. Bandyopadhyay and her team performed systematic rheological measurements to look at the effects of rotational shears on the viscosities of these suspensions for density-matched cornstarch suspensions that range between 35 wt.% and 42 wt.% in concentration. They also studied the dependence of the shear banding phenomenon on the thickness of the sample and found that with increasing thickness, the critical shear rate for forming shear bands increases.

In collaboration with Abhishek Dhar, Sanjib Sabhapandit and Prakhyat Hejmady, Bandyopadhyay studied size segregation in a quasi 2-D granular column. The dynamics of a large particle (intruder) in a 2-D vibrated column of small grains was studied. It was found that the intruder, which is initially kept at the bottom, rises upward when the column is vibrated. This particle was tracked as it moved upward using high speed video imaging to estimate its dynamics, including how relative density effects the rise time, velocity and acceleration of the large particle.

Building on earlier research, Bandyopadhyay and her team improved the design of the falling ball viscometer set up earlier so that the ball is now released via an electromagnet-based mechanism into Laponite suspensions. The terminal velocity at different Laponite ages is estimated, as is the microscopic viscosity of the Laponite suspensions (using Stokes Einstein law with corrections for wall effects and high Reynolds numbers).

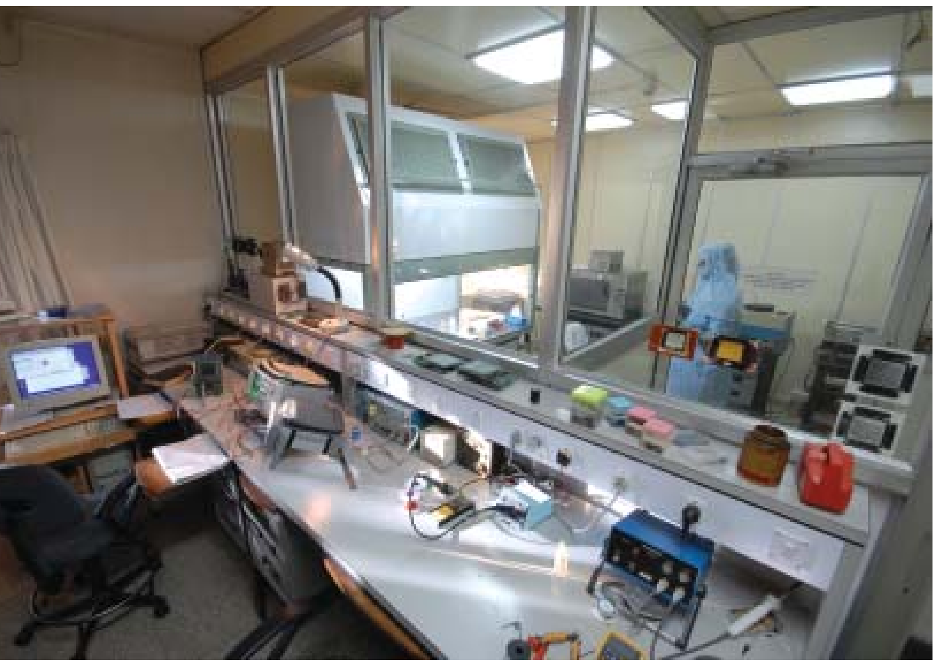
D Vijayaraghavan's research interests lie in the field of nanoparticle-liquid crystal composites and their physical properties. During the year, he concentrated his efforts on studying the physical properties of liquid crystal-nanoparticle composites, diamagnetic properties of lyotropic liquid crystals and high magnetic field experiments.

These physical studies were on a ternary lyotropic liquid crystal system. Lyotropic liquid crystalline phases are mostly exhibited by surfactant molecules dissolved in water under proper temperature-concentration conditions. The basic units of these systems are anisotropic micelles. Lyotropic liquid crystals find diverse applications from ordinary soaps to biophysics and in oil recovery. Their applications mainly depend on the concentration of the constituents and temperature. Therefore, it is imperative to understand their phase behaviour and their physical properties as a function of concentration and temperature. To this end, Vijayaraghavan carried out differential scanning calorimetry (DSC), mass diamagnetic susceptibility and electrical conductivity of a ternary lyotropic liquid crystal system consisting of sodium decyl sulfate (SdS)/decanol/water as a function of temperature for two different concentrations of the

constituents. It was found that, in these concentrations, the system exhibited calamitic nematic (Nc), isotropic (I) and hexagonal (H) liquid crystalline phases on heating from room temperature. The DSC thermograms exhibited two peaks that can be related to the reported Nc-I and I-H phase transition temperatures. However, on cooling from a high temperature, it was found that they did not show any peak, indicating the absence of liquid crystalline phases. The temperature dependence of magnetic susceptibility and electrical conductivity of both the samples also showed hysteresis.

Magnetic studies showed that the hysteresis was due to the changes in the sizes of the micelles; however, electrical studies showed that the hysteresis was due to the changes in the viscosity of water. This is an indication that water viscosity is related to the sizes of the micelles. Interestingly, in water-based nanofluids, the sizes of the suspended nanoparticles have a profound influence on the viscosity of water.

Mass diamagnetic susceptibility studies were also carried out on the ternary liquid crystal system for two different concentrations of the constituents (41.6/6.6/51.8 wt% – sample 1; 35.47/7/57.5 wt% – sample 2). It was seen that the isotropic phase susceptibility is temperature dependent at low temperatures and temperature independent at high temperatures for both samples; this can be related to the low temperature admixtured and high temperature pure isotropic phases reported for this sample. The susceptibility of sample 1 in the nematic phase is temperature independent while that of sample 2 is temperature dependent. Diamagnetic anisotropy of sample 1 is temperature independent while diamagnetic anisotropy of sample 2 is temperature dependent and it is about six times higher than that of sample 1 at room temperature. The increase in the shape anisotropy of the micelles in sample 2 due to higher concentration of decanol and lower concentration of SdS may be responsible for this observation. Alcohol and soap molecules are located mainly in the flat and curved portions of these prolate micelles, respectively. Increasing the concentration of decanol increases the flat portion of the micelles and decreasing the concentration of SdS decreases the curved portion of the micelles. It is inferred that the resulting change in the micellar shape lead to an increase in the shape anisotropy (length to diameter ratio) of these prolate micelles. This indicates that the diamagnetic anisotropy in the nematic phases of these systems can be fine tuned by a slight variation in their constituents. A marked change in the susceptibility of nematic and isotropic phases is observed on dispersing a small amount of single walled carbon nanotube in this lyotropic liquid crystal.



There has been considerable interest in bound water, or the water molecules bound to the micellar head groups or protein backbones through hydrogen bonding. Such molecules in the hydration shell around a protein play an important role in the protein's biological activity. Reorientational time correlation function of water dipoles around the protein molecules is calculated using atomistic molecular simulation and can be used as a tool to evaluate the bound water. For bulk water at room temperature (300 K) the water molecules' reorientation time is about 2 pS. When a small protein (1ETN) is added to bulk water, a decrease in the number of water molecules reorienting in the 1-2 pS range is found. This decrease is inferred to be related to the presence of bound water in the system. An increase in temperature showed a large decrease in the number of water molecules reorienting in the 1-2 pS range, thereby indicates that the bound water in the system increases with increase in temperature.

V Lakshminarayanan's research is largely conducted in the Electrochemistry and Surface Science Lab.

During the year, his research included the study of the kinetics of adsorption of enzymes on the surface of gold electrodes. Studying surface-immobolised enzyme–substrate interactions is important to understand enzyme kinetics and enzyme activity. It will also pave the way for the development of novel biosensors.

In this respect, electrochemical methods have an edge over commonly used optical methods. This is because the charges generated during the electrochemical reactions are reflected in the interfacial properties of the electrode–electrolyte system which then can be measured with relative ease. Lakshminarayanan, in collaboration with K Sankaran from Anna University and Shrikrishnan (VSP), used electrochemical impedance spectroscopy to study the kinetics of enzyme adsorption on the surface of gold electrodes. They investigated enzyme adsorption on two types of Self-Assembled Monolayers (SAMs) formed by an amino terminated thiol and a carboxylic acid terminated thiol. The adsorption of the enzyme calf intestine alkaline phosphatase was investigated using a newly developed EIS method that was confirmed independently using Quartz Crystal Microbalance (QCM) and Atomic Force Microscopy (AFM).

Along with Sandeep Kumar and research scholar BS Avinash, Lakshminarayanan covalently functionalized graphene oxide sheets with thiol and prepared thiolated graphene oxide self-assembled monolayer on gold surface. Electrochemical studies showed that the monolayer can partially block the electron transfer process. The method offers a way of integrating thiol chemistry with graphene chemistry to form modified surfaces that possess significant potential for the device development.

Ferrocene derivatives are interesting molecules for the study of redox reactions in soft matter as they can be easily solubilized. They also exhibit excellent redox mediators and can be formed, after suitable thiolation, as self-assembled monolayer films on gold and other noble metal surfaces. The electron transfer mediator properties are important from the point of view of electrochemical enzyme based sensor development. Lakshminarayanan and research scholars Anu Simon and Swamynathan studied the redox properties of some ferrocence derivatives on ferrocence hexane thiol self-assembled monolayers and showed that these properties are dependent on the dielectric properties of the solvent medium in which the reactions are carried out.

There is an ongoing effort worldwide to develop a low-cost, high-efficiency electrocatalyst for the oxygen evolution reaction as an alternative to the presently used platinum. As a follow-on of earlier studies, Lakshminarayanan and VSP student Chayanika Das are exploring the possibility of using the nanoparticles of nickel and cobalt as oxygen evolution catalysts. They are studying the enhancement in catalytic properties of the nanoparticles present on high surface area nickel and cobalt, with encouraging results.

One of the major research efforts of **Pramod Pullarkat**'s group is probing the mechanical and dynamical properties of axons. In particular, the group is interested in understanding the dynamics of the axonal cytoskeleton—a biopolymer network with force generating capacity—in generating active stresses and in controlling axonal morphology.

In order to probe the mechanical responses of axons the group is building a novel custom-made force apparatus. This set up, built in collaboration with Seshagiri Rao and with help from Chirag Kalelkar, uses an etched optical fiber to apply and measure forced in the range of a few pico Newton or higher. Using a feedback mechanism, it can be operated in a constant force (stress) mode or constant elongation (strain) mode. This device, which is akin to an Atomic Force Microscope, is built on a powerful microscope which allow for high resolution imaging techniques simultaneous with force measurement. The optical fiber based force measurement device was used to perform a couple of preliminary experiments. Fiber fluctuation due to Brownian dynamics was measured and analysed using liquids of different viscosities (water-glycerene mixtures). The data shows that the mean-square fluctuation amplitude that decreases with increasing viscosity. A theoretical understanding based on simple equipartition of energy predicts that the amplitude should be independent of viscosity. The inclusion of hydrodynamics or the effect of a wetting later may explain this discrepancy and these possibilities are being explored along with colleagues from the Theory Group. Apart from this surprising result, these experiments show that the setup is sensitive enough to detect thermal fluctuations in simple liquids at room temperature.

Another set of preliminary experiments was to probe active suspensions by monitoring the fiber fluctuations caused by bacterial suspensions. Swimming E-coli bacteria produce forces of about 1 pico Newton. It was noticed that the observed mean-square fluctuations depended on bacterial activity. Moreover, the fluctuation amplitude decreases when bacterial activity is reduced. Statistical analysis reveals significant deviations from pure Brownian dynamics and the nature of these deviations depends on the type of motion the particular strand of bacteria exhibits (tumbling vs. running).

In collaboration with Anagha Datar, Roli Srivatsava and the group of Aurnab Gosh from IISER, Pune, Pullarkat group performed experiments to quantify the beading process (also known as pearling instability) in axons of tissue-cultured neuronal cells. It was made clear that axons bead (develop peristaltic shape modulations) at a typical wavelength when microtubules—one of the biopolymer type in the cytoskeleton—are made to de-polymerized. The group is trying to understand the mechanism driving this beading process. A series of experiments employing biochemical techniques was performed to identify the cellular components relevant to this process. Fluorescence microscopy and genetic methods are also being performed. Preliminary data suggests that the beading may be driven by the active dynamics of the axonal cytoskeleton—a mechanism different from the recently studied Pearling Instability.

During the year, a new technique to measure mechanical properties and active dynamics of axons was tested. The idea was to quantify thermal (Brownian) fluctuations of an axon (one micron thick and 100-200 micron long) in order to extract its spring constant (elastic modulus). This method looked promising in our initial comparison between live axons and axons treated with a fixative which "freezes" the internal structure. Experiments with biochemically treated cells were more difficult to quantify. Pullarkat and his team plan to take this experiment further to see if the experimental methods can be improved to get over this difficulty.

Another research theme for the year included pattern formation in differentiating stem cells. This research aims at investigating stem cell differentiation in externally imposed chemical gradients (such as growth factors) and substrate stiffness gradients. This is being pursued in collaboration with Renu Vishavkarma, Maneesha Inamdar of JNCASR, and Jyotsna Dhawan of INSTEM. The aim is to mimic and study pattern formation in developing embryos using stem cells.

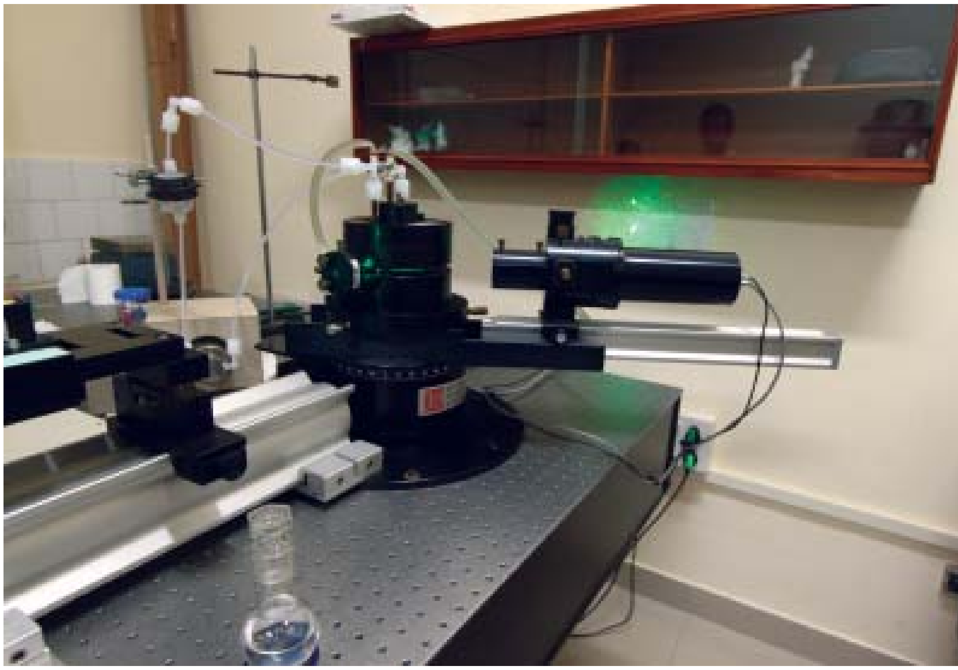
VA Raghunathan conducts fundamental experimental research in the area of structure and phase behaviour of soft matter systems. He is also involved in developing theoretical models of these systems to interpret the experimental results.

For the first time, a shear-induced phase transition was observed of lamellar (Lα) and isotropic phases (Lx) consisting of bilayers to a crystalline phase (Lc) in a lyotropic surfactant system. In-situ x-ray scattering measurements show that the transition to the crystalline phase is first order and reversible under shear. An increase in the isotropic to crystalline transition temperature with shear-rate is revealed in the shear diagram constructed from rheo-optical methods. It has been proposed that the imposed shear field increases the spontaneous curvature of the bilayers resulting in the unbinding and consequent redistribution of the hydrophobic counterions. This leads to a coexistence of a lamellar phase of reduced bilayer separation and a crystalline phase in the counterion-poor and counterion-rich regions of the bilayer, respectively. This study was done in collaboration with Rema Krishnaswamy of JNCASR and AK Sood of IISc.

Raghunathan's research during the year included a phenomenological theory of phase transitions in two-component lipid bilayers. Many lipids of biological origin self-assemble in water to form lamellar phases consisting of a periodic stack of bilayers separated by water. Different lamellar phases are observed as a function of temperature and water content. Raghunathan and PhD students Md. Arif Kamal and Antara Pal along with Madan Rao, recently developed a theory that is able to account for all the salient structural features of these phases.

This theory has now been extended to two-component lipid bilayers and different generic phase behaviours of these systems have been calculated. Phase diagrams of these systems have also been experimentally determined from x-ray diffraction data. Phase diagrams obtained from the theory are found to be in qualitative agreement with the experimental data.

Coacervates are concentrated colloidal dispersions coexisting with a dilute aqueous solution. Although they have been widely studied due to their importance in a variety of applications, their microstructure is still poorly understood. Raghunathan and his team observed the formation of a coacervate when an aqueous solution of the ionic surfactant alkenylsuccinic acid (ASA) is doped with small amounts of a non-ionic ethoxylated



surfactant. Coacervation resulted from the formation of hydrogen bonds between undissociated COOH groups of ASA and oxygens in the polyoxyethylene head groups of the non-ionic surfactant. Similar behaviour was observed when the non-ionic surfactant was replaced with polyoxyethylene of sufficiently high molecular weight. Small-angle x-ray scattering studies show that this phase is made up of bilayers with short-range positional correlations. Cryo scanning electron microscopy images of this phase show a sponge-like structure. Further studies are underway to find the structure of this phase consistent with the diffraction data and cryo-SEM images. This research was in collaboration with PhD student Antara Pal, and P Bharat and SG Dastidar of Unilever Research India.

Raghunathan and Pal studied coacervation of the anionic surfactant sodium dodecylsulphate on the addition of the organic salt, p-toluidine hydrogen chloride. At equimolar concentration of these two species, this system forms a dispersion of multilamellar vesicles (MLV) at low temperatures. On increasing the temperature, these MLV first transform into unilamellar vesicles, which on further heating form a coacervate. The coacervate shows flow birefringence and its diffraction pattern corresponds to bilayers with short-range positional correlations. Cryo scanning electron microscopy images of the coacervate show honeycomb-like structures. Further work is underway to elucidate the structure of the coacervate.

Many toxins, such as cholera toxin and shiga toxin, gain entry into the host cell by first binding and then inducing tubulation in the plasma membrane. Experiments using model membranes show that such tubulation occurs only with certain class of lipids. In order to understand the shape changes induced by these toxins in membranes, Raghunathan, PhD student S Madhukar and J Ludger of the Institute Curie in Paris, France, have studied the binding of these toxins to a membrane stack. On binding to the membrane, the toxin molecules are found to form highly ordered clusters. Further studies are underway to probe the shape changes of the bilayer induced by the bound toxin.

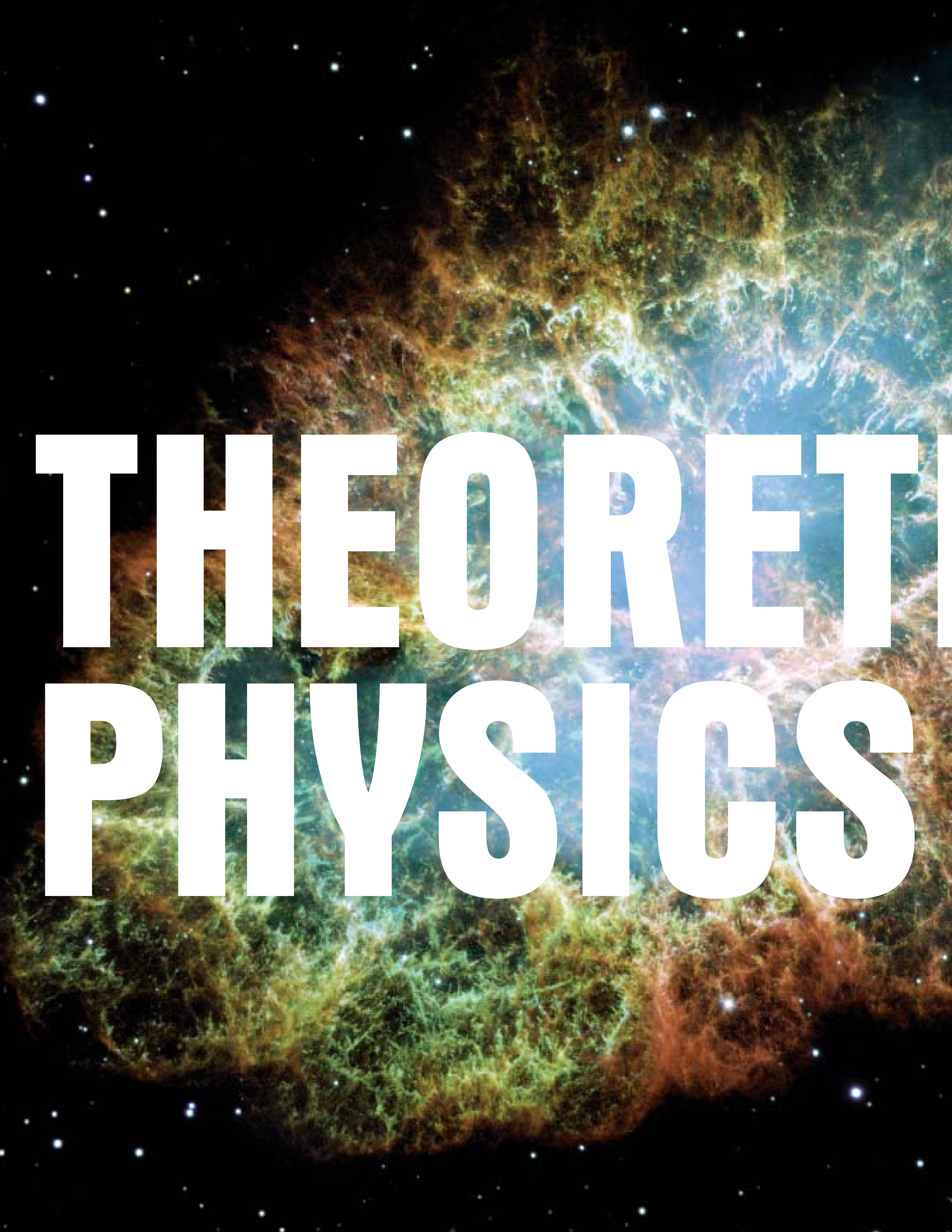
Amphiphilic molecules self-assemble in water to form aggregates of various morphologies, such as spheres, cylinders and bilayers. In addition to these well-known morphologies, some of these systems also form a network of cylinders over narrow regions of the phase diagram. Raghunathan and PhD student Santosh Prasad Gupta recently found surfactant-water systems consisting of a cationic surfactant and an organic additive, where such catenoid phases of different symmetries occur as a function of temperature/composition. The influence of the chemical structure of organic additives on the formation of catenoid phases was studied. Small changes in the structure of the organic additive are found to have a significant effect on the phase behaviour of the mixture. Current research is looking at the influence of these additives on the morphology of the surfactant micelles, in order to understand the formation and stability of the catenoid phases.

Post Doctoral Fellow **G Kavitha**'s work during the year included preliminary studies to develop the necessary instrumentation in a short timeframe and start studying the columnar liquid crystal systems. These were in collaboration with V. Lakshminarayanan, Arun Roy and Sandeep Kumar.

Developing organic photoconductors with suitably high charge carrier mobility is an interesting challenge. To achieve a fast and effective transport of charges through organic medium it is required that the charge carrier units are positioned such that sufficient mutual orbital overlap of the units is guaranteed. It is clear that only highly ordered system such as liquid crystals will fulfil this condition. For this, Kavitha focused on designing an instrument to measure the photoconductivity of liquid crystals. She and her collaborators successfully set up the direct photocurrent measurement with the function of temperature and started getting results from doped and undoped triphenylene derivatives. The photoconductivity measurement of doped and pure triphenylene derivatives was carried out for the first time.

It was found that after doping $HAuCl_4$, some triphenylene derivatives showed conductivity enhancement by several orders. Some of the photoconducting triphenylene derivatives showed significant enhancement due to the illumination of light. These results have been sent to the Elsevier journal.

During the year, Kavitha also conducted a study of carbon nanotube stabilised blue phase (BP) liquid crystals. The BP is believed to be based on a locally doubly-twisting structure in which the helix axis lies in all 360° directions. Depending on how the double-twist structure orient themselves in three dimensional space, BPs are further categorized into BPs I, II and III, which are body-centred cubic, simple cubic symmetry, and amorphous, respectively. BPs are attracting both scientific and technological interest with regard to the prospect of creating next generation optical devices utilising their fascinating optical characteristics such as iridescence and macroscopic optical isotropy. However, their complex structure also limits their temperature range to only a few Kelvin below the clearing point of the material, and as a result, recent research has focused on developing techniques to expand the temperature range of the BPs. In order to get the BP, Kavitha and her collaborators used a 50% mixture of E7 (multicomponent nematic mixture) CN (cholesteryl nonanoate). A single wall carbon nanotube was used to stabilize the BP, which was obtained at around 8°C. Supporting experiments being conducted include DSC, TEM and electrooptic studies.



THEORETI PHYSICS

ICAL OVERVIEW

Established in 1995, the Theoretical Physics (TP) group comprises research faculty, post doctoral fellows and students who work at the interface between mathematics and physics. There are two main areas of research – gravity and statistical mechanics. Areas of interest within statistical mechanics are mesoscopic physics, non-equilibrium physics, soft condensed matter physics and biophysics. Research in general relativity includes gravitational waves and quantum gravity.

Members often engage in collaborations among each other and/or groups of the institute that conduct experimental physics activities. The group has also created a forum for theorists to conduct simple table-top experiments that can express conceptual points.

The following pages summarize the major areas of research for the TP group. Each member's individual work during the last year is provided in the next section, giving the reader a more detailed and technical description of their respective research activities.

STATISTICAL MECHANICS

When a macroscopic device or a sample of bulk material is scaled down to mesoscopic size (from a few microns to the size of a single atom), they begin to reveal quantum mechanical effects. As a result, its properties might be very different from its parent material.

Research at RRI is focused on the development of a theory of heat and electron transport in such mesoscopic scale systems. Part of that work includes analytical and numerical treatment of Fourier's law of heat conduction in disordered harmonic and anharmonic crystals. Theoretical and experimental research in that field is important for the advancement of our fundamental understanding of the transport properties of materials, which in turn would lay the foundation needed to improve the performance of nanodevice applications and technologies.

The development of fast algorithms to estimate the probability of rare events is part of the ongoing research in the field of non-equilibrium statistical mechanics. Developed in the context of physics, such algorithms are also important in other areas of life like finance and cellular processes in biology.

BIOLOGICAL PHYSICS

Various topics in the field of biophysics have attracted the interest of the TP group, including mitochondrial distribution dynamics, vesicle formation and the development of analytical models to describe DNA elasticity (stretching, twisting and various deformations). Membranes and transport of materials in the cell are other topics that have been pursued at RRI. Research in biophysics involves active collaboration with experimental groups on campus and at the National Centre for Biological Sciences (NCBS) of TIFR.

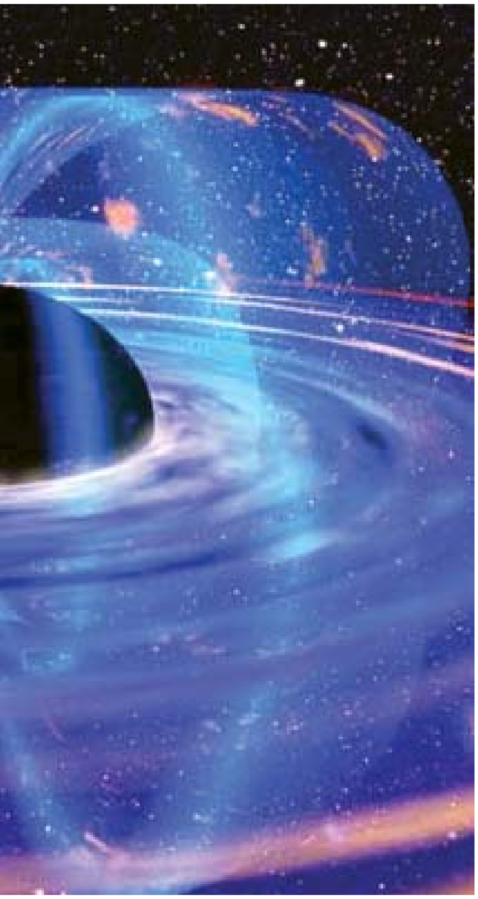
GRAVITATIONAL WAVES

The existence of gravitational waves was predicted by Albert Einstein's theory of general relativity in 1916. Their existence is inferred using indirect methods but they have not been measured directly yet. The direct detection of such waves will not only help scientists test general relativity more thoroughly but, more importantly, it will open up objects and phenomena in the universe that have thus far been invisible to optical and radio astronomy.

In general, sources of gravitational waves are bodies with a strong time dependent gravitational field. These sources include binary star systems composed of white dwarfs, neutron stars or black holes. The orbiting bodies of such systems continually lose energy while radiating gravitational waves. This leads to a decrease in the distance between the bodies, forcing them to rotate more rapidly and thus increasing their loss of energy to gravitational radiation. For systems like the Sun-Earth, one may calculate this effect and will find it to be negligible on the time scales of the universe. The closer the bodies in the binary system, the larger this effect is, leading eventually to a collision that can result in a merger or the creation of a black hole.

Such binaries are referred to as inspiralling binaries because the bodies in the binary system describe a spiral as they approach each other.

Laser Interferometer Gravitational-wave Observatory, or LIGO, is a joint scientific experimental project attempting to detect directly gravitational waves. The project is led by scientists and engineers from MIT, Caltech and other universities. VIRGO is another interferometer aimed at direct gravitational wave detection, and is the result of the effort of various European institutions. Both these instruments have been built and tested and have achieved their design sensitivities. The signals expected are extremely weak and buried in noise. A major challenge now is the accurate calculation of the expected gravitational waveforms from the observed binary systems. These waveforms will then be cross-correlated with the observational data to extract the gravitational wave signature. Researchers at RRI are currently looking at ways to precisely calculate the gravitational waveform from few inspiralling binaries. In the future, this research is expected to help improve the sensitivity of other envisioned space instruments aimed at detecting gravitational waves like LISA (Laser Interferometer Space Antenna).



QUANTUM GRAVITY

The formulation of a theory of quantum gravity has currently engaged the minds and creativity of a major part of the theoretical physics community. Quantum gravity (QG) is envisioned to be a self consistent theory that will quantize the gravity field, thus combining the two major theories of quantum mechanics and general relativity. There are a handful of QG theories being developed in parallel, like the string theory, loop quantum gravity and causal set theory. Research at RRI has focused on the last two approaches to quantum gravity.

Loop Quantum theory proposes that all the space where physical phenomena happen can be represented by the continuity of finite quantized loops of excited gravitational fields called spin networks. Unlike string theory, loop quantum gravity (LQG) doesn't try to unify all four major forces (electromagnetic, gravitational, strong nuclear and weak nuclear). The major challenge for LQG comes from the fact that quantum theory relies on a reference (background) space-time, while general relativity is said to be background independent. The approach of LQG is to formulate quantum mechanics without relying on the space-time reference. Members of the Theoretical Physics group at RRI develop new mathematical tools and ideas to get closer to the development of a true theory of quantum gravity.

Causal Set theory is another approach to quantum gravity. Its founding principle states that space-time is fundamentally discrete and the relations between space-time events are causal. Members at RRI focusing on causal set theory investigate classical stochastic growth modes, topology and dynamics of the causal set in their attempt to construct a consistent quantum theory of causal sets. Parallel to that, investigations of the observer-independent alternative formulation of quantum theory are currently being conducted.

In his early days, Einstein believed that the universe was static. His general relativity theory was predicting otherwise, so he added a term called the cosmological constant that made the universe static.

Later on, Hubble provided observational proof that the universe was expanding and Einstein abandoned the cosmological constant calling it the "biggest blunder" in his career. Recently, the interest in the cosmological constant among cosmologists and theoretical physicists has increased mainly because its inclusion as a cosmological parameter significantly improves the agreement between theory and observation.

The gravitational pull of matter is expected to slow down the expansion of the universe. Surprisingly, observations of supernovae indicate that the expansion of the universe is accelerating! Such results, though preliminary in nature, raise the possibility that the universe contains an unknown form of matter or energy that is gravitationally repulsive. The cosmological constant may describe such matter or energy, but a lot more work remains before cosmologists and theoretical physicists can throw light on this. Another reason for the reintroduction of the cosmological constant is that the estimated age of the universe (with the amount of matter we observe) by cosmological models that don't take it into account is less than the age of the oldest stars we observe. When the cosmological constant term is added to the standard theory of Big Bang it becomes consistent with various astronomical observations. Building on the work of Sorkin, who suggested that the observed cosmological constant may be due to quantum gravity fluctuations, researchers at RRI pursue an analogy between that elusive term in the theory of general relativity and the surface tension of fluid membranes. This is yet another example of the collaborations that emerge at the institute due to the interactions between members with different fields of research.

ONGOING RESEARCH

Sanjib Sabhapandit's research spans various topics of statistical physics, including statistical physics of out-of-equilibrium systems, disordered systems, stochastic processes, extreme value statistics, integer partitions, granular media, dynamics of polymers, and large deviations of rare events for various non-equilibrium additive processes.

During the last year, Sabhapandit studied the statistics of records for a time series generated by a continuous time random walk, and found them to be independent of the details of the jump length distribution, as long as the latter is continuous and symmetric. However, the statistics depend crucially on the nature of the waiting-time distribution. The probability of finding M records within a given time duration has a scaling form, and the exact scaling function is obtained in terms of the one-sided Lévy stable distribution. The mean of the ages of the records, defined as $\langle t/M \rangle$, differs from $t/\langle M \rangle$. The asymptotic behaviour of the shortest and the longest ages of the records were also studied.

He also studied large deviations of heat flow in harmonic chains along with his colleagues Anupam Kundu and Abhishek Dhar. The heat transport across a harmonic chain connected at its two ends to white-noise Langevin reservoirs at different temperatures was considered. In the steady state of this system, the heat Q flowing from one reservoir into the system in a finite time t has a distribution P(Q,t). Sabhapandit studied the large time form of the corresponding moment generating function $\langle \exp[-s Q] \rangle \sim g(s) \exp[t\, m(s)]$ and obtained exact formal expressions, in terms of phonon Green's functions, for both m(s) and the lowest order correction g(s). In general, a knowledge of both m(s) and g(s) is needed to find the large deviation function associated with P(Q,t). The function m(s) is known to be the largest eigenvalue of an appropriate Fokker-Planck type operator and this method also gives the corresponding eigenvector exactly.

Work on finding the probabilities of rare events in nonequilibrium processes, in collaboration with Abhishek Dhar and Anupam Kundu, was also continued during the year.

Abhishek Dhar's research interests span several areas in theoretical physics and he has worked in tandem with researchers from CEA in Grenoble, France, Tokyo University, University of California Santa Cruz, TIFR and RRI.

During the year, Dhar and his collaborators have extended the use of the Green-Kubo formula to study frequency-dependent thermal conductance. These results are expected to be useful in understanding nonequilibrium measurements of thermal conductivity in experiments on low dimensional systems.

Dhar and Keiji Saito from Tokyo University provided the first numerical verification of Fourier's law. Fourier's law of heat conduction is a phenomenological law and it does not have a rigorous microscopic derivation. The law is not known to be valid in low-dimensional systems in general, and there has been the question of what the necessary conditions are for Fourier's law to be valid in three-dimensional systems. In dielectric crystals, lattice vibrations (or phonons) are the carriers of heat and an important mechanism for scattering is via phonon-phonon interactions. To investigate whether this gives finite heat conductivity, Dhar and Saito performed non-equilibrium simulations of heat conduction in a three dimensional anharmonic lattice. It was found from numerical data that the three dimensional system has a finite thermal conductivity. The cross-over from one-dimensional to three dimensional behaviour of thermal conductivity was also examined.

In stochastic processes, there are events that occur with extremely rare probabilities. However, when they do occur, they can have severe consequences, and so it is important to be able to predict the precise probabilities of these rare events. A simple example would be the mutation of a gene under normal conditions. In the context of transport, Dhar, Sabhapandit of RRI and Kundu of CEA, France, have developed an algorithm to accurately and efficiently compute the probabilities of rare events such as the flow of current against a potential gradient.

The large deviation function (LDF) is an important quantity that carries information on fluctuations in nonequilibrium processes. In the context of transport, the LDF contains information on the steady state current and all moments of current-fluctuations in a system. A special symmetry property of the LDF is referred to as the fluctuation theorem, and seems to be satisfied in a large class of nonequilibrium processes. There are few examples of many-particle systems where the LDF has been analytically computed. Recent research of Dhar and his collaborators – Anupam Kundu, Keiji Saito and Sanjib Sabhapandit – included obtaining analytic expressions for the LDF for heat transport in arbitrary harmonic networks. They were also able to find the correction to the LDF for a one-dimensional harmonic chain, which is needed to establish the validity of the fluctuation theorem in this system.

The measurement of heat transport in low-dimensional systems such as nanowires, nanotubes and grapheme has garnered quite a bit of interest in recent times. This is due to the fact that properties of low-dimensional systems can be completely different from those of the bulk three-dimensional sample. Understanding transport properties is important with regard to technological applications such as developing nanodevices.

Some interesting data was recently obtained by a group in TIFR on thermal conductivity in n-type doped In-As nanowires. The most interesting result was that the thermal conductivity was about 1,000 times smaller than bulk samples while the electrical conductivity was almost unaffected. Secondly, it was

found that applied gate voltages had a strong effect on the thermal conductivity. Dhar and his collaborators from TIFR obtained some qualitative understanding of these results.

Supurna Sinha's areas of interest include statistical mechanics of semiflexible polymers, geometric phase and optics.

Her work during the year included research into tops and writhing DNA, done in collaboration with Joseph Samuel. The torsional elasticity of semiflexible polymers like DNA is of biological significance. Fuller began a mathematical treatment of this problem using the relation between link, twist and writhe, but was hindered by the non-local nature of the writhe. As a result, an analytic statistical mechanical treatment that takes into account thermal fluctuations in computing the partition function has not been possible. In this study, the well known analogy with the dynamics of tops has been used to show that when subjected to stretch and twist, the polymer configurations that dominate the partition function admit a local writhe formulation in the spirit of Fuller and thus provide an underlying justification for the use of Fuller's "local writhe expression". This has led to considerable mathematical simplification in solving theoretical models of DNA and elucidating their predictions. The results facilitate comparison of the theoretical models with single molecule micromanipulation experiments and computer simulations.

Experiments have been conducted on biopolymers like double stranded DNA, which twist and stretch single molecules to probe their elastic properties. Thermal fluctuations play an important role in determining molecular elastic properties, but a full theoretical treatment of the problem of twist elasticity of fluctuating ribbons using the simplest worm like chain model (WLC) remains elusive. Sinha's study of this problem involved first taking a mechanical approach and then incorporating thermal effects in a quadratic approximation applying the Gelfand-Yaglom (GY) method for computing fluctuation determinants. The study interpolates between mechanics and statistical mechanics in a controlled way and shows how profoundly thermal fluctuations affect the elasticity of semiflexible polymers.

The new results include:

- A detailed study of the minimum energy configurations with explicit expressions for their energy and writhe and plots of the extension versus link for these configurations
- A study of fluctuations around the local minima of energy and approximate analytical formulae

for the free energy of stretched twisted polymers derived by the GY method

Insights derived from the mechanical approach have been used to suggest calculational schemes that lead to an improved treatment of thermal fluctuations. From the derived formulae, predictions of the WLC model for molecular elasticity can be worked out for comparison against numerical simulations and experiments.

During the year, Sinha, Joseph Samuel and Poonam Mehta continued their research into the non-local Pancharatnam phase in two-photon interferometry. They proposed a polarised intensity interferometry experiment that measures the non-local Pancharatnam phase acquired by a pair of Hanbury Brown-Twiss photons. The setup involves two polarised thermal sources illuminating two polarised detectors. Varying the relative polarisation angle of the detectors introduces a two photon geometric phase. Local measurements at either detector do not reveal the effects of the phase, which is an optical analogue of the multiparticle Aharonov-Bohm effect. The geometric phase sheds light on the three slit experiment and suggests ways of tuning entanglement.

She also studied atom interferometers and the gravitational redshift, along with Samuel. From the principle of equivalence, Einstein predicted that clocks slow down in a gravitational field. Since the general theory of relativity is based on the principle of equivalence, it is essential to test this prediction accurately. Muller, Peters and Chu claim that a reinterpretation of decade-old experiments with atom interferometers leads to a sensitive test of this gravitational redshift effect at the Compton frequency. Wolf et al dispute this claim and adduce arguments against it. In this study, these arguments are distilled to a single fundamental objection: an atom is not a clock ticking at the Compton frequency. It is concluded that atom interferometry experiments conducted to date do not yield such sensitive tests of the gravitational redshift. The study suggests a new interferometric method to probe gravitational redshift.

Joseph Samuel is a mathematical physicist who works in the fields of general relativity, optics and soft condensed matter physics. He uses geometry and topology to describe physical phenomena.

One of his interests is the elasticity and statistical mechanics of DNA. His research during the past year included understanding DNA elasticity using the standard techniques of statistical mechanics. While experiments do exist, their interpretation requires special attention due to the geometric and topological subtleties of the Writhe. This work, in collaboration with Supurna Sinha, examines the effect of thermal fluctuations on the statistical mechanics of DNA by using the Gelfand-Yaglom method for computing fluctuation determinants.

Under the field of gravitation, Samuel worked on atom interferometers and the gravitational redshift, in collaboration with Sinha. The aim of this study was to determine whether atom interferometry can be used to accurately test the redshift effect by critically examining the idea of a clock in general relativity. The study leads to a proposal of a new class of experiments in gravitation which study the interference of quantum clocks.

Bala Iyer's principal research interests are in the field of general relativity. He has been studying the computation of high accuracy gravitational waveforms for ICB using multipolar post-Minkowskian methods. These high accuracy post-Newtonian (PN) waveforms have resulted in the construction of GW templates for GW data analysis. They are also vital to validate recent numerical waveforms of plunge merger and ringdown and assess their accuracy and interpretation.

Inspiralling compact binaries (ICB) of neutron stars and black holes are the most promising sources of gravitational waves (GWs) for terrestrial laser interferometer GW detectors like LIGO and VIRGO and space detectors like LISA. GW signals are very weak and buried in the detector noise and can only be extracted and characterized using techniques like matched filtering.

During the year, Iyer, in collaboration with CK Mishra and KG Arun from the Chennai Mathematical Institute, studied the 2.5PN linear momentum flux and recoil from ICBs in circular orbits.

Anisotropic emission of GWs from ICBs results in a loss of linear momentum and hence gravitational recoil of the binary system. The loss rate of linear momentum in the far zone of a nonspinning binary system of black holes in a quasi-circular orbit was investigated at a 2.5PN order. This was used to provide an analytical expression in harmonic coordinates for the 2.5PN accurate recoil velocity of the binary system in the inspiral phase of its evolution.

The 2.5PN computations are more involved due to the presence of hereditary terms in addition to the more familiar instantaneous terms. The maximum recoil velocity of the binary system at the end of its inspiral phase is of the order of 4 km/s and smaller than the 2PN estimate. Iyer and his collaborators also provided an estimate of the maximum recoil velocity at the end of the plunge (involving contributions both from the inspiral and plunge phases) for a binary with symmetric mass ratio 0.2 is of the order of 183 km/s.

Madhavan Varadarajan's research interests are in the field of classical and quantum gravity.

He continued his research into the issue of information loss in two-dimensional black holes, in collaboration with A Ashtekar from Penn State University and V Taveras from Louisiana State University. The research is in its final stages and a new outcome during the last year was the construction of a mechanism for information recovery in the four-dimensional collapse situation. This used the idea of "rapid" singularity resolution and seemed to evade the standard arguments against such recovery.

Varadarajan has also continued his work towards the construction of an anomaly-free quantum dynamics for Loop Quantum Gravity (LQG).

The recent formulation of the Parameterized Field Theory (a covariant reformulation of two-dimensional flat spacetime free scalar field theory) using an LQG

type 'polymer' model formed its basis. Physical states were constructed, without intermediate regularization structures, by averaging over the group of gauge transformations generated by the constraints (the constraint algebra was a Lie algebra). Varadarajan and post-doctoral fellow Alok Laddha considered classically equivalent combinations of these constraints corresponding to a diffeomorphism and a Hamiltonian constraint, which, as in gravity, define a Dirac algebra.

The findings included the fact that the (triangulated) Hamiltonian constraint acts only on vertices, its construction involves some of the same ambiguities as in LQG and its action on diffeomorphism invariant states admits a continuum limit.

Varadarajan and Laddha also constructed the smeared diffeomorphism constraint operator at finite triangulation from the basic holonomy-flux operators of LQG, evaluate its continuum limit on the Lewandowski-Marolf habitat and show that the action of the continuum operator provides an anomaly free representation of the Lie algebra of diffeomorphisms of the 3-manifold.

The results of this analysis indicate a conceptual similarity between LQG and the so-called "mu-bar" scheme of Loop Quantum Cosmology.

During the year, **Sumati Surya** studied Markov Chain Monte Carlo (MCMC) methods for Causal Set quantum gravity in collaboration with Joe Henson of Imperial College, London, David Rideout of University of California San Jose and Rafael Sorkin of Perimeter Institute.

MCMC methods have proven to be very important in probing the structure of quantum gravity, a successful example of this being the Causal Dynamical Triangulation (CDT) approach to quantum gravity. In that approach, extensive numerical work has been carried out and there is a strong suggestion that the theory generates a universe much like ours with a positive cosmological constant. The MCMC methods can also be used in the Causal Set approach to quantum gravity, which begins from a very different set of first principles. Using these techniques, Surya and her collaborators looked into whether Causal Set Theory (CST) belongs to a different universality class than the CDT approach, or whether the physics at intermediate scales, which they both describe, is the same.

A suite of numerical algorithms for using MCMC for causal sets was constructed using the Cactus framework for the general case. Results confirm the predicted dominance of entropic configurations in the infinite temperature limit. For finite temperatures, analytic arguments show that entropic dominance is suppressed by the causal set action in four-dimensions. However, it was shown that the simulations take too long to thermalise, and the Markov chain remains in the high entropy configurations. The main reason is that the high entropy configurations have a specific order theoretic structure, which does not change under the class of moves considered. Attempts are on to consider a more suitable class of moves which could help achieve thermalisation.

The analysis of the 2-dimensional models of causal set quantum gravity using MCMC methods was initiated and a suite of numerical algorithms constructed using the Cactus framework. It was shown that this simplified model of causal set quantum gravity overcomes many of the hurdles present in the general case. In particular, it was shown to be computationally erdogic and to therefore thermalise rapidly. Several tests were carried out to establish the stability of the code and the ergodicity of the Markov process. Recent progress indicates the existence of a new layered quantum gravity phase, and investigations are continuing to confirm this.

In early universe models of cosmology, like inflation, a strong assumption is made about the nature of interactions even at scales much smaller than the GUT scale. However, "mesoscale" effects from quantum gravity can have a strong influence on the nature of these interactions even at non-Plankian energies. An example of this is non-locality which arises from causal set theory. Work has been initiated in understanding the role of a causal set induced non-locality in early universe cosmology in conjunction with Robert Brandenberger of McGill University and Rafael Sorkin.

It is vital to quantum gravity to be able to construct covariant observables in a measurement independent framework. In the causal set approach, such observables can be constructed using the quantum measure, and Surya's recently developed formalism makes it possible to answer concrete questions. It was shown that not all admissible dynamics allow the construction of a formally complete set of observables. However, it was seen that a weaker criterion may be applied which gives a physically meaningful class of observables (as opposed to a formally complete set). Efforts are on to understand whether this weaker criterion also limits the class of dynamics in collaboration with Rafael Sorkin and Fay Dowker and Steven Johnston of Imperial College.

Poonam Mehta is a Post Doctoral Fellow whose research interests touch upon the various theoretical and phenomenological aspects related to neutrinos – one of the most elemental and hard-to-detect elemental particles. She is also interested in geometric phases in neutrino oscillations. As neutrinos exhibit sustained quantum coherence over astrophysical length scales, researchers are interested in the properties of these particles in these coherent phases.

During the year, Mehta and Walter Winter of Wuerzburg University, Germany, looked into the importance of flavor ratio measurements in neutrino telescopes. The detected flavor ratios carry the energy information of specific new physics scenarios that alter the transition probabilities in distinctive ways, as well as the energy dependent flavor composition at the source. Mehta and Winter studied the interplay of these two energy-dependent effects and identified which new physics scenarios can be distinguished from the detected flavor ratios as a function of astrophysical parameters. The study was done using a self-consistent neutrino production model.

Other areas of Mehta's research during the year include the issue of obtaining large mixing in the neutrino sector as revealed by low energy data in left-right symmetric models and the characterisation of geometric phases in three-flavor neutrino oscillations.

Ryuichi Fujita is a Post Doctoral Fellow whose research interests include the study of gravitational waves and general relativity. He worked on the derivation of the gravitational waveforms needed to compute the 14th post-Newtonian (14PN) order energy flux in a circular orbit around a Schwarzschild black hole. The 14PN expressions will lead to the parameter estimation comparable to numerical waveforms for extreme mass ratio inspirals, which are one of the main targets of Laser Interferometer Space Antenna (LISA).

Fujita also derived the fitting formulae of the rates of change of constants of motion and the associated rates of change of orbital elements due to gravitational radiation by a test particle in eccentric inclined orbits around a Kerr black hole.

Such formulae are useful to construct a template bank of gravitational waves from extreme mass ratio inspirals and develop an algorithm for LISA data analysis since the computation of numerical waveforms is very expensive and may be bypassed by the formulae.

Roman Sverdlov is a Post Doctoral Fellow whose research interests include quantum gravity and causal set theory.

One of his major topics of research during the year was including particle creation and annihilation into deterministic Pilot Wave model. Generalizing the Pilot Wave model to second quantization is difficult, unlike the well-know first quantization, since creation and annihilation of particles is a "discrete" process and is not easy to view deterministically. Sverdlov proposed the introduction of extra compactified coordinate to overcome this difficulty.

Whenever the particle is on one side of the "semicircle", it is visible. When it is on the "other side", it is invisible. Thus, its trajectory in that extra coordinate is differentiable (and, therefore, can be deterministic). However, when the particle "crosses" the "line" between two semicircles, its visibility undergoes a "discrete jump". The timing of that jump can be predicted and, therefore, determinism is preserved. But this, unfortunately, requires the allowance of gross non-locality, which is far "worse" than non-localities present in other Pilot Wave models and results in a trade-off between having to face unwanted non-locality and preserving desired determinism.

Sverdlov also encoded the mathematical information about configuration or Fock spaces within ordinary, three dimensional space. This was done by discretizing the former, while leaving the latter in a continuum form, thus making sure that it has "less information" than the latter. He is also studying the combination of the Bohmian and Ghirardi-Rimini-Weber (GRW) approaches in such a way that each "cures" some of the shortcomings of the other. His approach involves taking the collapse mechanism proposed by GRW and modifying it in such a way that it is centered around the Bohmian particle.

Post Doctoral Fellow **Samarth Chandra**'s professional research interests include spin glasses and biophysics.

In collaboration with Barry Richmond of National Institutes of Health in the US, Chandra explored models for the effect of the absolute refractory period of a neuron on the statistics of its spike train. They were able to construct simple models, two of which they were able to solve analytically while another model was mapped to a well-studied problem in queueing theory. They also explored the question of what should be the dynamical rules for the processing of spikes by a neuron so that an incoming Poisson spike train leads to a Poisson spike train as output.

Chandra's other research theme included exploring the behaviour of spin glasses as a function of spin space dimension. He found that the behaviour of spin glasses changes significantly at specific spin space dimensions. Connection of this result to protein folding and structural glasses has been explored.

Laboratories

Radio Astronomy Lab (RAL)

The Radio Astronomy Lab (RAL) at RRI consists of three divisions – Digital Signal Processing (DSP) Lab, Millimeter Wave and RF Lab, and X-Ray Astronomy Lab.

DSP Lab

The DSP lab is involved in the design, development and testing of digital receivers for astronomy. The DSP lab team comprises skilled engineers with expertise in the field of digital circuit design and digital signal processing. RRI has a long history of design and development of a variety of digital systems (receivers, spectrometers, correlators) that have improved the capabilities of national and international telescope facilities. The lab has modern CAD design packages for the development of FPGA-based digital systems.

Millimeter Wave and RF Lab

The engineers from the RF lab are experienced professionals with diverse skill-sets in the design and development of millimeter wave and RF systems. The lab is equipped with all necessary fabrication and testing facilities for RF systems characterisation. The group has designed and built feeds, broadband antennas as well as standard and special purpose front end receiver systems operating at wavelengths from decameter to millimeter.

X-Ray Astronomy Lab

The X-ray lab is a fully equipped laboratory for development and testing of X-ray astronomical instrumentation. The infrastructure includes a clean room, X-ray generator, beam line, polarizer and monochromator, vacuum systems, mounts and electronics for performance evaluation of X-ray detectors.

FACILITIES

LAMP Group Labs

Each faculty member of the LAMP group at RRI runs lab facilities specific to his/her individual research.These four labs are:

- The Laser Cooling, Light Scattering Lab
- The Ultrafast and Nonlinear Optics Lab
- The Quantum Optics Lab
- The Quantum Interactions (QUAINT) Lab

The well-established facilities for laser cooling and trapping of atoms include vacuum systems, commercial and custom-made lasers, spectroscopy equipment, standard electronics and real time operating systems. The lab that hosts an experimental system to investigate quantum walks of light consists of three Michelson optical interferometers, various optical components and acoustic-optical modulator. Two labs allow for experimental research of nonlinear optical properties of nanocomposites and dynamics, and spectral behaviour of laser induced plasmas. Standard and custom-made facilities in the lab include a femtosecond laser system with amplifier, nanosecond Nd:YAG laser, spectrometers, monochromators, laser beam profiler, ultra high vacuum chamber, X-ray and Gamma-Ray detectors, experimental set up for z-scan and pump probe measurements, and more.

SCM Group Labs

Chemistry Lab

The lab has state of the art facilities necessary for the synthesis and structure characterisation of novel liquid crystal materials. Major equipment in the lab includes polarizing optical microscopes, high performance liquid chromatograph, differential scanning calorimeter, elemental analyser, infrared and UV-Visible spectrophotometer. Over 700 mesomorphic molecules have been synthesised and characterised in the Organic Chemistry Lab at RRI.

Physical Measurements Lab

The Physical Measurements Lab is equipped with standard facilities for phase transition studies in liquid crystals, liquid crystal nanocomposites and various micellar solutions. The lab members are actively involved in the development of new precise techniques for a variety of phase transition measurements. Available equipment include a polarising optical microscope, dielectric impedance analyzer and confocal microscope. Currently, there are experimental set ups for conoscopic, switching current and various electro-optical measurements.

Liquid Crystal Display Lab

The LCD lab has basic facilities for fabrication of liquid crystal cells and small size (100mmX100mm) displays as well as standard electronics equipment for their testing. Spin coating system, vacuum deposition unit, rubbing machine and temperature controlled ovens are frequently used by the lab members.

Rheology and Light Scattering Lab

The lab utilizes rheology and light scattering techniques to study the dynamics of soft glassy materials and amphiphilic systems. The most frequently used instrumentation in the lab includes a dynamic light scatterometer and a rheometer. Rheology, dynamic light scatterometry and diffusing wave spectroscopy are some of the measurement techniques used in the lab.

X-Ray Diffraction Lab

The X-ray lab is set up for investigating the phase behaviour of various surfactants using X-ray diffraction. Polarizing light microscopy and small angle X-ray scattering techniques are often used in the lab. To perform precise X-ray measurements, the lab is equipped with a confocal microscope, X-ray

diffractometer and a small angle X-ray scatterometer.

Biophysics Lab

The Biophysics lab is a self-sufficient lab where various cells can be grown, manipulated and analyzed. It is equipped with two fully motorised microscopes allowing for fluorescence and face contrast microscopy measurements, confocal microscope, biosafety cabinet for growing cells, incubators, centrifuge and a 3D microscope for dissections.

Electrochemistry and Surface Science Lab

The lab performs controlled experiments on test surfaces in electrochemical cells using electrochemical instruments such as a potestiostat, frequency response analyzer and lock-in amplifier. An electrochemical quartz crystal microbalance is used to measure mass changes. Thin film characterisation is done with a variety of scanning probe techniques like scanning tunnelling microscopy, atomic force microscopy and others.

Mechanical Engineering

The mechanical workshop at RRI meets the mechanical design and fabrication needs of RRI experimental activities. It has the necessary machinery and a team of skilled personnel who can undertake fabrication of various sophisticated mechanical hardware components for electronics instrumentation as well as sheet metal work for component, receiver enclosures, and system racks. The expertise of the mechanical workshop team has been used in large projects like the fabrication and installation of 1100 helical antennas for the Mauritius Radio telescope, design and fabrication of a low frequency antenna feed system for GMRT, and fabrication of a multi-band feed for the Green Bank telescope, West Virginia. Specific tasks such as fabrication of precision mounts, positioners and cooling stages for the LAMP and SCM groups have been undertaken by the mechanical workshop team as well.

Library

The library at RRI was founded by Sir C V Raman and ever since has served as a constant source of both highly specialized and general knowledge for the institute members. Throughout the years, the library has continuously expanded trying to provide adequate literature for the growing research activities at RRI.

Currently, its total collection of books and bound journals is close to 65,800. The library has an extensive collection of materials in the areas of research conducted at RRI – astronomy and astrophysics, classical and quantum optics, soft condensed matter, theoretical physics, electronics, digital signal processing, computer science, etc. The non-book materials of the library include scientific slides, CD-ROMs, DVDs and audio and video tapes.

The RRI library is a partner in both FORSA and CSIR-DST consortia and the expansion of full text access to online journals is one of its major priorities. It also maintains a digital repository of all publications published by RRI members as well as students' theses and dissertations. Open Public Access Catalogue (OPAC) is available for access to readers within and outside RRI. The library participates in inter library networking activities with various other institutions like the Indian Institute of Science, Indian Institute of Astrophysics, Jawaharlal Nehru Centre for Advanced Scientific Research, National Aerospace Laboratories, National Centre for Biological Sciences, TIFR Centre for Applicable Mathematics and others.

Last year, the library repository continued to grow. It added 456 books, most of which were scientific, but also included some of a more general nature: 48 Hindi books, 25 gratis books and 19 non-book materials. The library subscribed to 76 print journals and 83 online journals. 609 bound volumes of journals were added to the library.

The library continued to provide need-based information services to users and maintained liaison with many local and outside libraries. Various subscriptions through FORSA and the National Knowledge Resource Consortium of CSIR-DST facilitated enhanced access to over 4,000 online journals.

Digitization of archival material, such as hand-written manuscripts, letters and photos, has been taken up and will be uploaded to the RRI Digital Repository. Nearly 110 papers published during the year have been uploaded. The RRI Digital Repository currently holds 3,938 items.

Computer Facilities

The various computing needs of the different research and development groups at Raman Research Institute are handled by our computer division team. The computing facilities consist of multi-CPU multi-core systems accessed by users from their desktops through a high speed internal LAN.

Application-specific software packages along with development tools are available on these platforms. The campus network consists of a switched Gigabit backbone on fiber and wired 10/100 Mbps Ethernet to the desktops.

Further mobility is assured by the secured wireless connection available on the campus premises. A dedicated 10 Mbps line ensures the constant connectivity to the global Internet community. A computer center is also available in the library for the needs of students, staff and visitors.

The computer facilities on campus continued to be upgraded and improved during the last year. The eight node cluster was replaced with a high performance computer cluster with 16 nodes. System and application packages were upgraded, and the network security improved. Backup and storage requirements were addressed to meet increased storage needs.

Operating system upgrades were undertaken for key servers, and scientific and other application packages were procured and upgraded. Wi-Fi access on campus was made more secure by employing the more secure WPA2 protocol. Security aspects of our servers were re-examined to reduce threats to our network from outside. Internet access was shifted to the high speed link provided by the National Knowledge Network.

In addition, a two-day workshop on Parallel and Distributed Computing was organized in association with CDAC Bangalore.

Campus

The Raman Research Institute campus is located in the northern part of Bangalore city. The campus covers an area of around 20 acres, where the bustling noise of the fast growing metropolis gives way to the soothing sounds of nature, creating the necessary peaceful environment for creative work and research. The campus hosts all the office buildings, laboratories, a canteen, guest house and the 10.4m telescope but when walking around one is left with the impression that they are all tiny additions to the prevailing natural garden.

Most of the campus was landscaped by Sir C V Raman and the RRI Trust is proud to enforce policies that protect its unique natural environment. The guest house on campus has facilities to comfortably accommodate distinguished visitors and visiting academics, including visiting doctoral students. A canteen is also present on campus to provide meals to all guests as well as lunch and refreshments to all RRI employees. Various gatherings, visitor talks, informal meetings, concerts and dinners take place at the Village – an ethnically designed area providing a warm rustic touch to the overall atmosphere on campus.

The building adjacent to the canteen houses a small clinic where consultant medical practitioners pay visits at fixed hours on most working days of the week. Sports activities are envisioned to be an important part of campus life. Therefore, there are two badminton courts available for use by the research faculty, staff and students. Extensive renovations of major facilities and buildings on campus have been taking place during the last couple of years. The Auditorium in the Main building was equipped with better lighting and sound technology, and while addressing the issues of water seepage and de-stressing the building, it was decided while tackling these issues, to construct a creative space on the Library building rooftop. The

canteen building underwent major renovations to modernize and upgrade it to provide quality service to the institute members and distinguished visitors in a faster and more efficient manner.

PhD Programme

RRI offers a PhD programme that gives enthusiastic and motivated students the opportunity to join the global research community. The unique atmosphere of intellectual freedom allows the students at RRI to pursue their individual interests within the broad areas of research conducted at the Institute. As a result, students are challenged to engage their full creative potential and develop the ability for conducting independent research. Constant formal and informal interactions with the faculty and other students take the learning process outside of the classroom and individuals' office space, encouraging students to think and question critically others' and their own understanding and knowledge. Such interactions also promote an open minded attitude towards science and research. Attendance at national and international conferences exposes RRI students to a much larger and diverse research community where they get a perspective of what the "big picture" in their field of research is.

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

Currently, there are nearly 60 students from all over India enrolled in the PhD programme and conducting research with faculty members from the four groups in the institute. Last year five PhD degrees were awarded and five were submitted for review.

Post-Doctoral Fellowship Programme

RRI offers a post doctoral fellowship programme which is open for applications throughout the year. The initial duration of the post doctoral fellowships is two years and is often extended to three years. Post-doctoral fellows work independently and have the academic freedom of choice in research area and collaboration. Even though post doctoral fellows are not required to work in any specific research programme or be attached to specific research staff of the Institute, it is desirable that they have professional research interest and proven track record in areas with significant overlap or association with the ongoing and envisaged activities at the Institute. Participation of the fellows in the academic activities of the Institute,

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student supervision as co-guides and collaboration with other research staff is highly encouraged.

Candidates who have already held at least one position as a post doctoral researcher can also apply for a limited number of Pancharatnam Fellowships offered at RRI. Applications are accepted throughout the year and the processing time takes between four to six months. The selected candidates are awarded the Pancharatnam Fellowship for a period of three years.

Further details about the Post Doctoral and Pancharatnam fellowships at RRI can be found on the website www.rri.res.in.

Currently, there are twelve post doctoral fellows at RRI coming from across the country and abroad. Their research background, diverse scientific interests and future goals play important role in the overall academic and research dynamics of the institute.

Visiting Students Programme

Raman Research Institute places high importance on its Visiting Student Programme (VSP) which was introduced in 2007. VSP at RRI offers research experience to students, who are currently pursuing their undergraduate or master's studies. The programme runs year-round and its duration ranges from 6 weeks up to one year depending on individual cases. At the beginning a suitable project is identified for each student. While working on their projects, VSP students are closely advised by a research faculty or scientific staff member of the Institute. They are encouraged to interact with other staff members and graduate students learning the importance of sharing knowledge and exchange of ideas among researchers. The programme is designed such that students get exposed to some of the real challenges in the world of scientific research and acquire important skills that would help them in their future research pursuits.

The Summer Student Programme at RRI is similar to the Visiting Student Programme but it runs only between May 1st and June 30th of each year. It provides the opportunity to upto twenty selected candidates to become involved in short term research projects under the guidance of a research faculty member.

Since the programme initiation, the number of VSP students has progressively increased through the years. During the year, a total of 112 students from different parts of the country were part of the VSP at RRI. The duration of these programs ranged between six weeks to six months, and sometimes, even a whole year. All those interested to join the VSP at RRI should visit our website to learn more about the eligibility criteria and application process.

PROGRAMS

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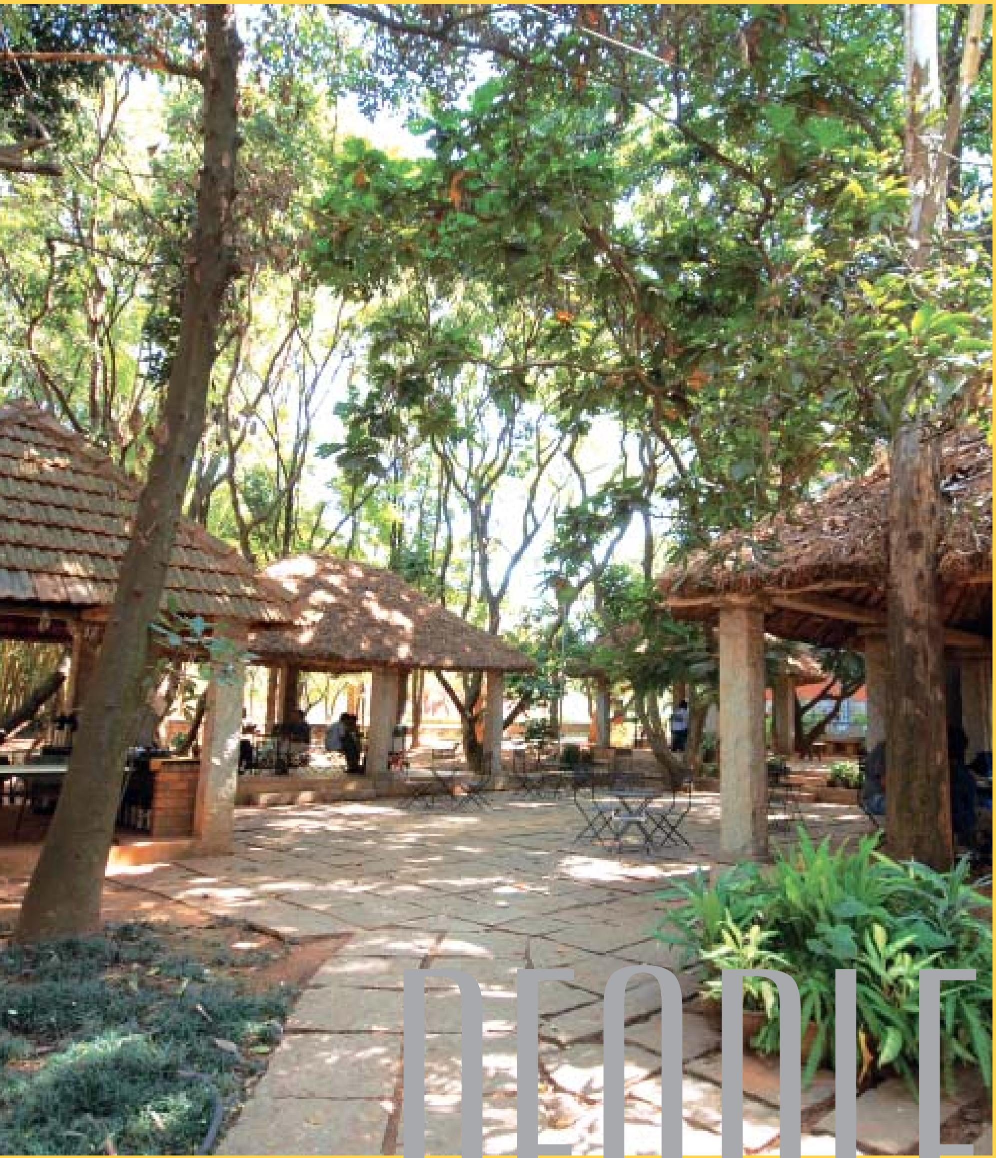

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C N Ganapathy (In-charge)
B M Basavarajaiah
U A Earappa
H Gangaiah
Keshavamurthy
Suresha
K Krishnappa
Munihobalaiah
K Pushparaj
O M Ramachandra
G Ramakrishna
M Sannaiah
H Vaderappa
S Nagaraja (Consultant)

Transport

C N Ganapathy (In-charge)
M K Raju Kutty
M Balarama
K Mohanan
G Prakash
Rahamath Pasha
G Raja
M Venkateshappa

Amenities

(Guest House & Hostels)
Shivamallu
Mangala Singh
Muniratna
T Naganna
N Narayanappa (In charge)
D B Padmavathy
P C Prabhakar
N Puttaswamy
A Raju
N Seetharam
Uma
Sharadamma
Yashodha
Srihari Prahlad (GHC)

Horticulture

Bylappa
Govind K Kundagol
Lingegowda
D Mahalinga
Mailarappa
Marappa
D Muniraja
S Muniraju
Rahamathulla Khan
Rangalakshmi
Varalakshmi

Medical

Consultant Paediatrician:
Dr. M R Baliga
Consultant Physician:
Dr. B V Sanjay Rao
Technician:
R Shanthamma

Carpentry

M Gopinath
L Muthu (Expired 9.2.2011)

Gauribidanur Telescope

Support Staff
Bheema Naik
Gangaram
M Muniyappa
Papanna
Prahallada Rao
R P Ramji Naik
Ranoji Rao
Shivarudraradhya
Thippanna
Venkataswamy
N R Srinath

PUBLICATIONS

The institute publishes the research activities carried out over the year in national and international peer-reviewed journals. Each of the four research groups at RRI finds their work published in distinguished journals that focus on their specific research area. For the Theoretical Physics group these include, but are not limited to, Physical Review, Classical and Quantum Gravity, Journal of Physics, Journal of Statistical Mechanics and Biophysics Journal. Research faculty and students from the Soft Condensed Matter group have their work published in journals like Physical Review, Liquid Crystals, Journal of Physical Chemistry, Journal of Chemical Sciences, Journal of Applied Physics, European Physical Journal, Journal of Nanoscience and Nanotechnology and many more.

Publications of the Light and Matter Physics group at RRI can be found in Physical Review, Journal of Nanophotonics, Optical Express and Canadian Journal of Physics. The astronomers and astrophysicists at RRI use the Physical Review, Monthly Notices of the Royal Astronomical Society, Astrophysical Journal, the Journal of Astrophysics and Astronomy and others as a means to share their work with the scientific community around the world. One hundred and four papers featuring RRI members as their authors and/or co-authors were published during the year. There were 14 publications in conference proceedings and 40 (38 in journals and 2 in conference proceedings) publications are in press. Members at the institute expand and diversify their work beyond the scope of highly specialized technical and science journals by publishing books and/or articles for popular science magazines. (Appendix I)

OTHER ACTIVITIES

Conferences

Conferences and visits to various institutions at home and abroad play a significant role in the research activities of the institute members. Such events provide opportunities for idea exchange and are often a starting point for future fruitful collaborations with other researchers from various institutions within India and abroad. Last year, faculty and students of the institute attended numerous conferences in India, Australia, Israel, Japan, the US and all over Europe.

In addition, lectures and invited talks were given at a variety of workshops, international programs, multinational project meetings and training programs. Members of the Institute visited colleges around the country and specially organized workshops on different science and research topics to deliver lectures, talks and presentations.

A full list of the conferences visited by each of the institute members is provided in Appendix II.

Seminars and Colloquia

Thursday colloquia are one of the numerous activities promoted at the Institute as a way to increase the interactions between the various research groups within RRI as well as those between RRI members and invited speakers and their institutions. Apart from covering relevant science topics, the colloquia often introduce new and interesting themes from various other disciplines.

During the last year, the Institute invited speakers from all over India, the US, Japan, Korea, Singapore, Australia, Italy, Denmark, Germany, Switzerland and the UK to deliver the Thursday colloquia. The topics included the likes of "Quantum Games", "Looking for Primordial Non-Gaussian Signals in the CMB", "Nanocatalysts and Their Applications", The Evolution Animal Grouping and Collective Motion", and "From Darkness, Light: Computing Cosmic Reionization".

A complete list of the speakers, their lecture topics and when they visited RRI is given in Appendix III.

Seminars at the Institute are often delivered by visiting faculty and researchers. Unlike colloquia, seminars are intended to deepen the understanding and generate discussions on a very specific research theme. Usually, the topics cover the current progress of collaborative projects between RRI and the visitor's institution, or themes of particular interest to RRI members.

A list of the visiting research faculty and researchers to RRI during the last year, is given in Appendix IV.

Visiting Scholars

A high priority is given to increasing the stream of visiting scholars to the institute. In today's high-tech world of global connectivity the academic and research community is more open then ever before. Maintaining nationally and internationally open environment is crucial for the success of every research institution.

Members at RRI recognize that and work tirelessly toward creating more opportunities for larger number of scientists, researchers and engineers to visit the institute, contribute new ideas and skills, while benefitting from the expertise of our own members. Visits at RRI can last from few days to few months and often lead to important collaborative results and/or the conception of new interesting projects.

Last year , there were more than 100 scholars who visited RRI from 18 Indian and more than 30 international institutions. RRI is happy to have so many friends and thanks all of them for making the environment in the institute so diverse, dynamic and vibrant.

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

Journal Club

The Journal Club at RRI, initiated in 1981, aims at drawing the attention of members of the Institute to exciting and interesting papers that appear in scientific literature. Given the large numbers of papers published these days, it is nearly impossible for an individual to keep track of developments outside their research specialities. The Journal Club tries to partly remedy this situation by presentations of a variety of recent papers of general interest.

The last Journal Club slot of the year is traditionally reserved to review the year's Nobel Prize Award in

Physics. While speakers present their selected papers, informal discussions, questions and demonstrations are strongly encouraged as often they are the seeds of better understanding that can lead to better quality research.

A list of the papers reviewed during the Journal Club meetings last year is attached to the annual report as Appendix V.

Hindi Cell

RRI has initiated its efforts to reach the targets fixed by the official language policy of the Government of India. In this direction, training in Hindi was continued in addition to holding workshops and participating in activities in the neighbouring institutions. Efforts were also made to incorporate Hindi in the account statements and to adopt the same in purchase reports. Efforts to meet the targets laid down by the Official Language Policy in the administration of the Institute were intensified. Efforts to make the targets laid down by the Official Language Policy in the administration of the institute were intensified.

Reservations

The institute follows the reservation policy as is followed by the Government of India and scientific departments like Department of Space and Department of Atomic Energy.

Others

The RRI community is involved in various other activities ranging from organizing special conferences, meetings and workshops, and inviting college students to the campus, to having formal and informal dinners, sport tournaments, and a variety of cultural programs both with invited performers or members of RRI itself. Such activities are considered to be an integral part of the members' experience at the institute. Other events and activities such as in-house meetings, concerts, formal faculty farewell dinners, college visits and more continue to enrich and diversify the academic life and atmosphere at the Raman Research Institute.