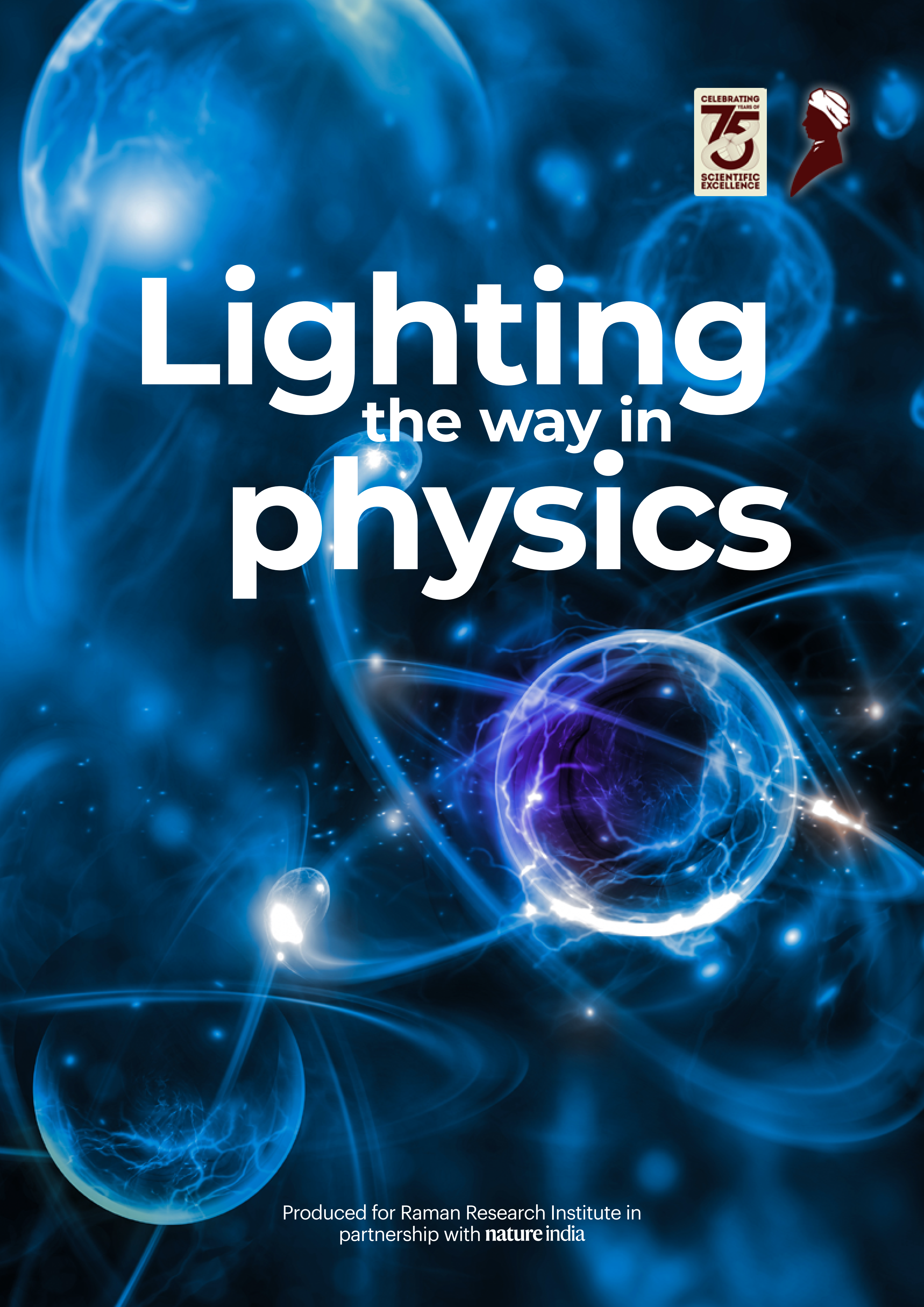

CELEBRATING 75 YEARS OF SCIENTIFIC EXCELLENCE

Lighting the way in physics

Produced for Raman Research Institute in
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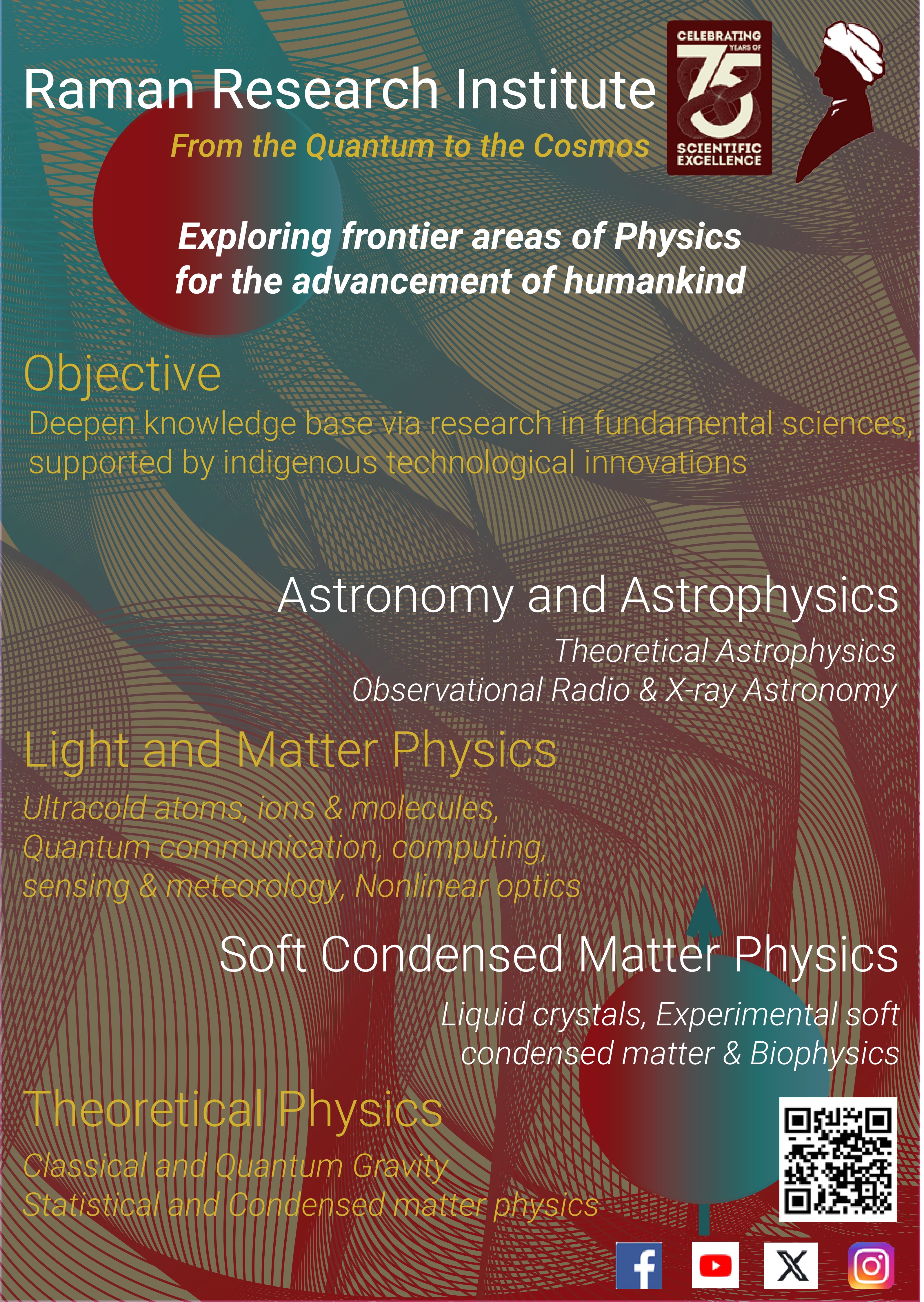

Raman Research Institute

From the Quantum to the Cosmos

CELEBRATING 75 YEARS OF SCIENTIFIC EXCELLENCE

Exploring frontier areas of Physics for the advancement of humankind

Objective

Deepen knowledge base via research in fundamental sciences, supported by indigenous technological innovations

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Theoretical Astrophysics
Observational Radio & X-ray Astronomy

Light and Matter Physics

Ultracold atoms, ions & molecules,
Quantum communication, computing,
sensing & meteorology, Nonlinear optics

Soft Condensed Matter Physics

Liquid crystals, Experimental soft
condensed matter & Biophysics

Theoretical Physics

Classical and Quantum Gravity
Statistical and Condensed matter physics

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Reflections on a journey of discovery

Raman Research Institute (RRI), founded in 1948 by physicist and Nobel Laureate, Sir Chandrasekhara Venkata Raman, is celebrating 75 glorious years. To mark this historic occasion, Nature India and RRI have put together a special commemorative volume to highlight some of the landmark explorations in the institute's history.

RRI is focused on astronomy and astrophysics, light and matter physics, soft condensed matter and theoretical physics. The institute is responsible for many firsts – from the 1977 discovery of discotic liquid crystals, to the validation of gravitational waves based on the prediction of the 'chirp' and 'ring down' signals when black holes merge. RRI scientists have helped build India's first millimetre wave telescope, providing key electronics to the world-class telescope facilities like the Murchison Widefield Array, Giant Metrewave Radio Telescope and the Square Kilometre Array. Their work has shaped the AstroSat and the forthcoming POLIX missions of the Indian Space Research Organisation. RRI is also at the forefront of developing quantum-enabled technologies and bio-sensing devices.

For this volume, we chose 15 of the most significant scientific articles published by RRI scientists over the years and invited reflections about them by their original authors or experts in the field. These examine RRI's frontline scientific offerings to the world and their wider historical implications. The authors discuss the merit of these papers in the context of global advances in physics.

Some articles in this issue talk about the ground-breaking work at RRI that set the bar for low radio frequency telescopic observations of the Milky Way, and explore the historic collaborations that led to improved ways to image the skies. Some others analyse the scenario in which a pulsar – a highly magnetised rotating neutron star – can be resurrected from its cosmic graveyard, and dwell on a landmark investigation into the decay of neutron star magnetic fields. A couple of commentaries look at research that examines the cosmic dawn, and consider recent work that aids the measurement of gravitational waves.

Authors of this volume remember how the discovery of discoid liquid crystals in the 1970s paved the way for a new generation of organic electronics, and how they came to explore the properties of an extraordinary class of mesomorphic materials called bent-core liquid crystals. Readers will get a glimpse of the backstory of a 2021 paper which outlined a simple molecular model for ferroelectric nematic liquid crystals, and trace the evolution of our understanding of the physical properties of chiral smectic liquid crystals, which light up LCD screens.

The issue investigates cutting-edge research on self-assembling nanocarriers that are revolutionising drug delivery, and discusses a theoretical model for the cell membrane that includes the driving forces of actin, the most abundant protein in our bodies. We hear of other scientific frontiers that RRI has crossed — from delicate geometrical nuances in quantum systems to a new approach to investigating phonon transport in nanowires, and the discovery of dual cooling mechanisms in a mixed ion–atom system.

We acknowledge the role of senior academicians, whose advice was immensely helpful in selecting from among the many impactful research articles that have emerged over the 75 glorious years in this institute's scientific history. We hope readers enjoy these stories that blend history and cutting-edge physics, the essence of this anniversary volume.

Subhra Priyadarshini
Editor-in-chief
Nature India

Tarun Souradeep
Director
Raman Research Institute

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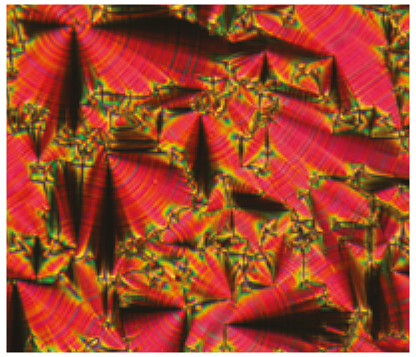

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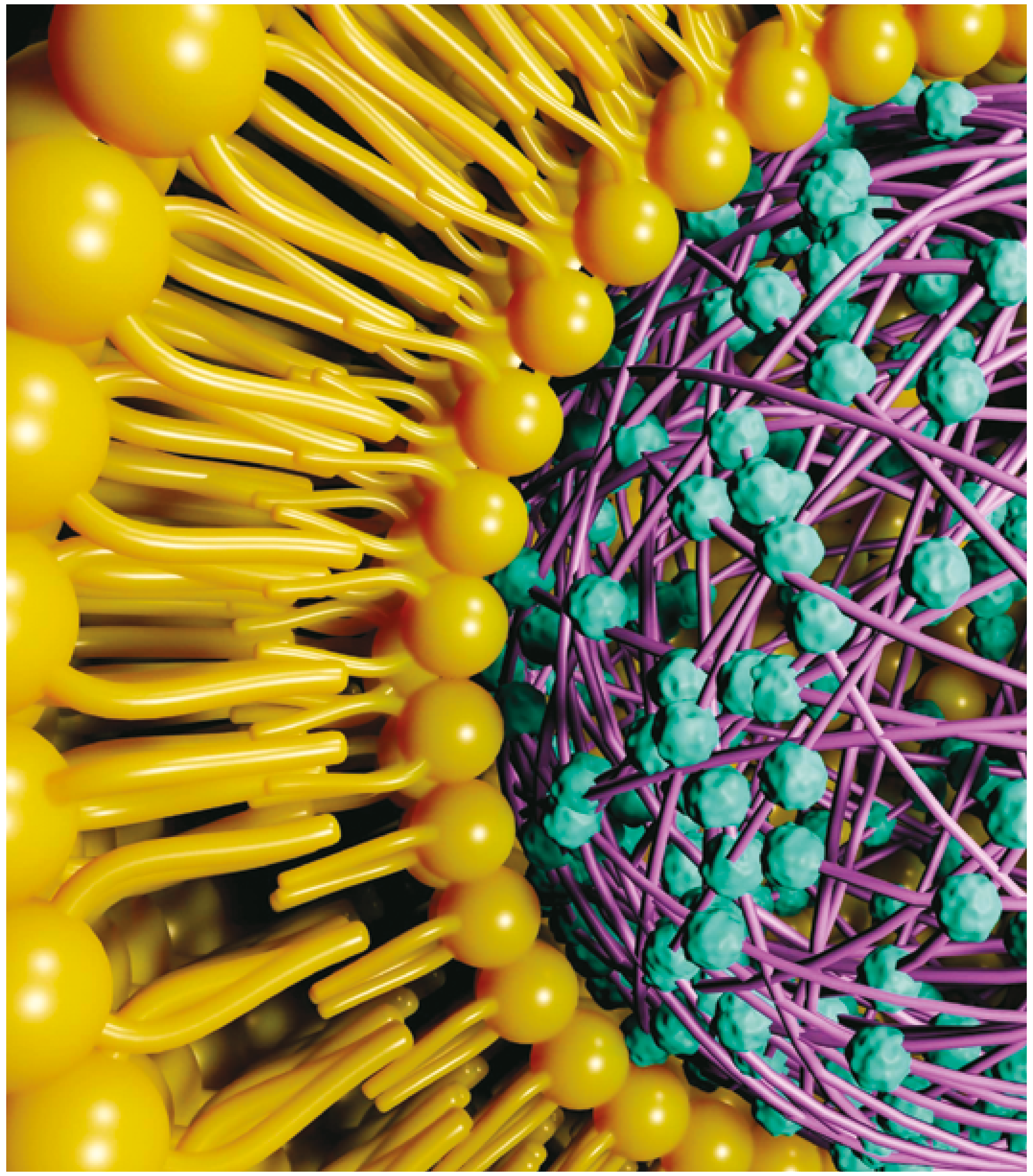

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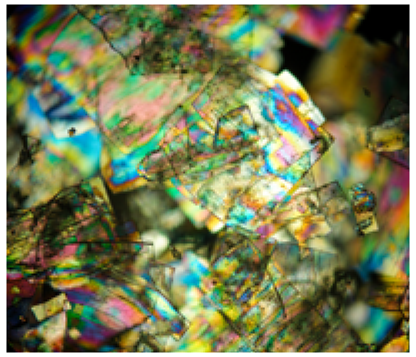

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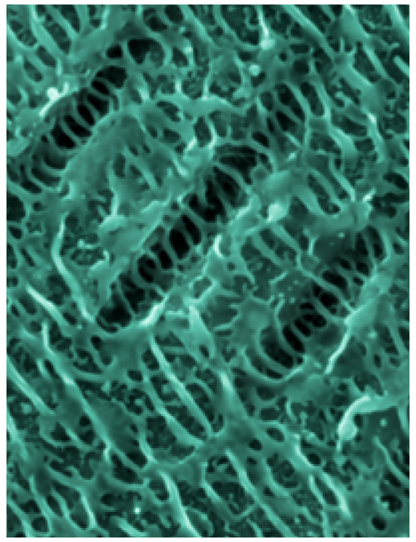

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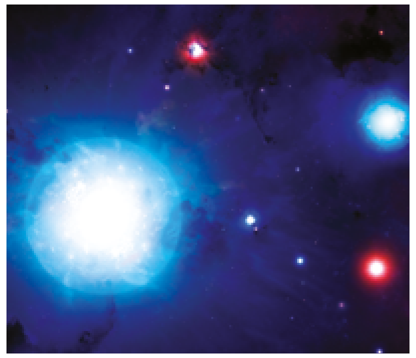

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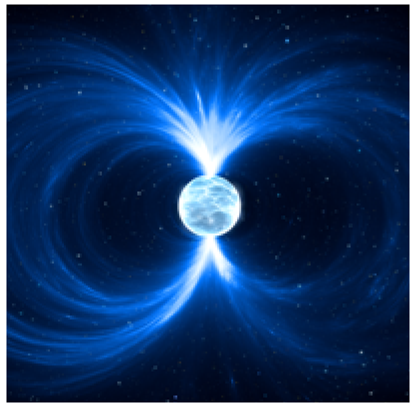

The low radio frequency survey that imaged the sky in one day

Ground-breaking work at the Raman Research Institute in the 1980s set the bar for low radio frequency telescopic observations of the Milky Way

K S Dwarakanath

The low radio frequency sky survey was one of the important research projects at the Raman Research Institute (RRI) during the early 1980s. Its main purpose was to image the radio emission from the Milky Way and from the extragalactic sources as accurately as possible. By the end of the 1980s, it was possible to produce a survey of the sky at low radio frequencies by using the Gauribidanur radio telescope working at 34.5 MHz (a wavelength of about 8.7 metres)

Radio astronomy began at low frequencies in the early 1930s when Karl Jansky used an antenna that received radio waves at 20.5 MHz. The quest for better angular resolution soon saw radio astronomers using much higher radio frequencies – about 1,000 MHz – since it was easier to achieve higher angular resolutions with relatively smaller apertures at shorter wavelengths.

There were many attempts to image large regions of the sky at different sites around the world, including an array at 38 MHz in Cambridge in the UK during 1966, the Penticton array in Canada at 10 MHz during 1976 and the Clark Lake array in the United States at 26 MHz during 1988. These observations were plagued with problems such as varying instrumental and ionospheric conditions and interference from terrestrial radio signals over the days, weeks and months of observing the sky. They were also unable to image the extended radio emission from the Milky Way.

The sky survey at RRI set out to overcome these shortcomings. The dipole array situated at Gauribidanur was 1.4 km along the east-west arm and 0.5 km along the south arm. Special multi-channel receivers were built to record signals from each of the 90 dipoles along the south array and were multiplied by the signal from the east-west array. This novel technique allowed the entire observable sky to be imaged in just one day.

The effects of solar and ionospheric activities and terrestrial radio frequency interference were minimised by choosing days that were most suitable for the observations. Furthermore, a novel technique adopted in analysing the images minimised the instrumental response in the images.

This survey was a unique opportunity for students at the RRI to learn and master radio astronomy. The students built and successfully used all the hardware and software needed for the survey, which gave them invaluable experience that went way beyond what they could have learnt from books. The students who worked on this project went on to lead research activities in diverse areas of astronomy all over the world.

This survey firmly established low frequency radio astronomy in India and led to RRI's involvement in building the Mauritius radio telescope working at 150 Mhz and in contributing to building the Murchison Widefield Array in Western Australia working in the range of 80–250 MHz.

The RRI survey produced a reliable image of the sky at low frequencies with an angular resolution of about half a degree by half a degree (about the size of the full moon). It has become one of the reference points in the study of radio emission from the Milky Way at low frequencies.

As an illustration of how low the frequency used in the survey was, I recall a conversation with an astronomer who worked at the Karl G Jansky Very Large Array (VLA) in the United States in the early 1990s. When I told him that I had worked at low frequencies, he assumed that I was an expert working in the VLA L-band. The L-band referred to radio frequencies around 1,500 MHz. I sheepishly told him that I had worked at 30 MHz — only 50 times lower than the VLA L-band. ■

The Very Large Array, one of the world's premier astronomical radio observatories, consists of 27 antennas in a Y-shaped configuration on the Plains of San Agustin, New Mexico.

NRAO

An impression of a disc formed as the dust and gas in the galaxy falls on to a supermassive black hole, attracted by its gravity.

NASNJPL-CALTECH

The long walk towards gravitational wave phasing for inspiralling compact binaries

The continuing quest to decipher and measure gravitational waves

Bala Iyer

Albert Einstein arrived at the famous non-linear relativistic general relativity (GR) theory in November 1915. One year later, working in linear approximation, he proposed the existence of gravitational waves (GW) as one of the theory's important consequences. In 1918, he calculated – to leading order – the emission of GWs and the corresponding flux of energy far from source in his well-known quadrupole formula for gravitational radiation.[1] Computing GW emission beyond the leading order involves dealing with non-linearities of Einstein's equations and including effects of higher-order velocity. The accuracy of analytical GW emission calculations beyond the leading-order quadrupole formula are labelled by the 'post-Newtonian' (PN) order $v^2/c^2 \sim GM/c^2r$.

Russell Hulse and Joseph Taylor discovered the binary pulsar[2] 1913+16 in 1974. Discovery of binary systems with strong self-gravity mandated improved approaches to the 'two-body problem' requiring theorists to go beyond 1PN or v^2/c^2 relativistic effects in the equation of motion to 2.5PN or (v^5/c^5) due to the radiation reaction. High-quality binary pulsar data at that time forced scientists to revisit the approximation methods in GR[3] to fix the mathematical shortcomings in the existing approaches[4].

In the approach under consideration, the two compact objects in the binary are modelled as point particles since it can be argued that the tidal deformations are of higher order (5PN). The use of delta functions to model point particles in a non-linear theory leads to ultraviolet divergences and specific methods are needed for self-field regularisation. The discovery of 1913+16 and the paradigm shift from narrow band bar detectors to broadband laser interferometric GW detectors also changed the sources from supernovas to coalescing compact binaries (CCB) of neutron stars and black holes.

However, a detailed understanding of detector noise in the relevant frequency band of Hz-kHz indicates that GW from these CCB correspond to the situation of a weak signal buried in strong detector noise. Consequently, one requires techniques such as matched filtering to extract the signal from the noisy data and subsequently determine its parameters. For matched filtering to be efficient, accurate knowledge of the phase of the signal is needed, which as the system becomes more relativistic requires higher order corrections in velocity and hence higher orders in non-linearity GW.

Following funding of the Laser Interferometer Gravitational-Wave Observatory (LIGO) in the United States, work on constructing templates for GW detection were intensely investigated by Kip Thorne's group at the California Institute of Technology and summarised in an article evocatively titled *The last three minutes: issues in gravitational wave measurements of coalescing compact binaries*[5].

Thorne convened an international meeting in 1994 to brainstorm this issue and highlight the need to address this problem. Luc Blanchet and I were participants at this meeting as was Sanjeev Dhurandhar. Blanchet soon demonstrated the 2PN generation of GW and this led to a collaboration with him, Thibault Damour and me to compute the GW flux to order $(v/c)^4$ beyond the Einstein formula and provide the calculation of 2PN phasing for inspiralling compact binaries [6].

The new insight it required was the careful treatment of the cubic non-linearities in Einstein's equations. The availability of the 2PN equation of motion from the binary pulsar work facilitated the computation of 2PN phasing of CCB by two independent methods[7]: the multipolar post-Minkowskian and post-Newtonian (MPM-PN) method used above and the direct integration of relaxed Einstein equations (DIRE) by Clifford Will and Alan Wiseman[8] in the United States. A global virtual outpost for GW computations critical for the unforgiving GW experiments was coming to life. Data analysis pipelines for the initial detectors could be put in place based on these 2PN results.

The rather quick extension to 2PN phasing mistakenly led one to believe the extension to 3PN, required to deal with the more relativistic binary black hole systems, would be straightforward. Control of this 3PN order turned out to be more formidable due to the unexpected limitation of earlier regularisation methods for the self-field. Only after almost a decade of struggle and by complementing computations using Hadamard regularisation by the use of the gauge invariant dimensional regularisation[9] was the problem finally resolved and completed[10].

These results are the starting inputs for validating the early phases of the numerical relativity waveforms of CCB and the construction of extensions using the effective one-body and phenomenological approaches to describe merger and ringdown. Thus they play a critical role in the construction of templates for detection and parameter estimation and the basis for tests of gravity (TOG) using GW observations. The MPM-PN work is referred to in Kip Thorne's Nobel lecture. The PN and TOG publications are quoted in the GW discovery papers[11] and were the foundation of the current Indian presence in TOG activity in the LIGO-Virgo collaboration.

Currently MPM-PN is the most successful, since it can deal with all aspects of the required computations: the conservative equation of motion, radiation field at infinity, non-linear effects related to tails, tails of tails and non-linear memory. It has evolved over the last 30 years into a consistent algorithmic approach to analytical GW computations. MPM-PN and numerical relativity are the scaffolds underlying the impressive arch of effective one-body and Phenom template families used for detection, parameter estimation and TOG. The 3.5PN results have been the workhorse for the community until now since the tour de force of 4.5PN phasing was completed only recently[12]. At 4PN order a new feature arises: infrared regularisation plays a crucial role in addition to self-field regularisation. The 3.5PN phasing, 3PN modes[13] for quasi-circular motion were followed by extensions to 3PN evolution[14] and modes[15] for quasi-elliptical motion.

> *"The new insight it required was the careful treatment of the cubic non-linearities in Einstein's equations."*

On the Indian front, this work on source modelling at the Raman Research Institute was complemented by significant contributions to GW data analysis in a group led by Dhurandhar at the Inter-University Centre for Astronomy and Astrophysics. The aspiration to extend this Indian footprint in GW source modelling and data analysis to GW experiments motivated the formation of the Indian Initiative in Gravitational-wave Observations (IndIGO) consortium in 2009. This led to the LIGO-India proposal in 2011, IndIGO presence in the GW discovery and in-principle approval of LIGO-India in 2016 and finally the LIGO-India approval in 2023. ■

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Geometry and quantum interference

Joseph Samuel on the general setting for Berry's phase


Forces originating from the geometry of quantum mechanics may be useful to make smaller atom traps and better atomic clocks.

BRUCE ROLFF / ALAMY STOCK PHOTO

During a meeting of the Raman Institute Journal Club in the 1980s, my colleague Chandrakant Shukre and I were reviewing papers on quantum physics. Michael Berry from the University of Bristol had discovered a delicate geometrical effect appearing in quantum systems in a slowly changing environment.[1] The crystallographer Sivaraj Ramaseshan was in the audience and felt a sense of déjà vu. Further investigation revealed that Shivaramakrishnan Pancharatnam's work on polarised light[2] had anticipated Berry's findings by three decades.[3]

Quantum mechanics deals with matter waves, which share some features with waves you may see in a pond or hear in a concert hall. When waves meet, they can reinforce each other or cancel each other out. The determining factor is the phase of the waves and whether the two waves are in step or out of step. Berry found that in a cyclic change of the environment there was an extra geometric contribution to the phase. This effect can be detected in interference experiments. The Berry phase has since proved a seminal idea in optics, mechanics and condensed matter physics.

When I was invited to speak about the Berry phase at a meeting on the foundations of quantum mechanics at the Centre for Theoretical Studies, Bangalore, I presented Pancharatnam's work in the language of differential geometry. I had attended lectures on differential geometry by the distinguished Indian mathematicians Mudumbai Narasimhan and Sundararaman Ramanan who spoke about the theory of fibre bundles. I learnt the geometric interpretation of a *connection*, which is well known in mathematical circles.

A fibre bundle is a space which is locally a product of two spaces, but it is globally twisted. The simplest example is a Mobius strip. The centre line of the Mobius strip is a circle called the base space and the line perpendicular to it is called the 'fibre'. The fibre twists around and reverses itself as it goes around the base circle. A 'connection' is a rule for comparing points on two fibres. This mathematics applies to quantum physics and polarised optics: the fibres carry the phase information and removing the phase information gives us the base, which is known in physics as the ray space.

During the discussion after my talk, I realised that not everyone in the physics community appreciated the geometric nature of connections. Most physicists think of them as ungainly objects transforming awkwardly under gauge transformations. There was a clear need for a differential geometric treatment of the Berry phase informed by Pancharatnam's work on the interference of polarised light.

There was also a need for an experimental demonstration of Pancharatnam's ideas on the interference of polarised light. Pancharatnam had noticed the fine interplay between the connection and the geodesics – the shortest paths – in the base. I suggested to my colleague Rajendra Bhandari that a laser beam passed through optical elements like polaroids to make a geodesic triangle, would reveal the Pancharatnam phase in interference experiments. Bhandari, who had made precision laser measurements on the surface accuracy of a radio telescope, had the required experimental skills to take up the challenge. This resulted in a paper that we submitted to Physical Review Letters (PRL).[4] It was well received and was published in 1988.

The theoretical paper on the same topic that we submitted to PRL did not sail as smoothly.[5] There was opposition from within as well as without. As I was preparing the paper, there was a vocal minority of my colleagues demanding to know what was 'new' in the paper. One said it was full of 'mathematical jargon' and contained nothing of substance. One of the referees was scathing and dismissive and the paper was deemed unsuitable for publication. I replied with a point-by-point rebuttal. One of the problems was that the referee was unfamiliar with Pancharatnam's work. After some verbal fencing, the paper was accepted, published and began to have an impact. It was especially well received in Italy where there is a strong tradition in differential geometry. The paper has been reprinted in a curated collection – Geometric Phases in Physics – translated into Italian and over the years it has floated serenely into the good graces of the wider scientific community – so much so that it is sometimes cited even when it need not be. This success stimulated several research groups in India to start working on the geometric phase.

> *"There was a need for a differential geometric treatment of the Berry phase informed by Pancharatnam's work."*

Looking back, the work brings out a continuity in scientific research between the Raman era and the subsequent phase of the Raman Research Institute. Pancharatnam worked with Chandrasekhara Venkata Raman in the 1950s, and his ideas were rooted in experiments rather than fibre bundles. His thinking was both extremely precise and general. It was mathematics expressed in chiselled prose. Such clarity often leads to general perspectives far beyond the original context. The theoretical paper draws on this tradition and combines it with the modern differential geometric tradition of the Tata Institute of Fundamental Research where Narasimhan and Ramanan studied. Both traditions are firmly rooted in Indian soil. In fact, the modern differential geometric approach enables one to go beyond Pancharatnam's original ideas and offers a much more general and larger perspective.

In my work, I try to maintain a harmonious balance of abstract geometric ideas with concrete experiments. The elegance of mathematical abstraction combined with experimental demonstration weaves rigour and relevance firmly together. The same mathematics describe the geometry of quantum mechanics and purely classical problems. It can be used to describe the arcane art of parallel parking and the amazing grace and ability of falling cats to right themselves.

More recently in an investigation into the theory of closure invariants in radio astronomy[6], we suggest the use of the geometry of special relativity to glean uncorrupted information from noisy data to enable polarised imaging of black holes in the event horizon telescope. I have also suggested that the forces originating from the geometry of quantum mechanics may be useful to make smaller atom traps and better atomic clocks.[7] ■

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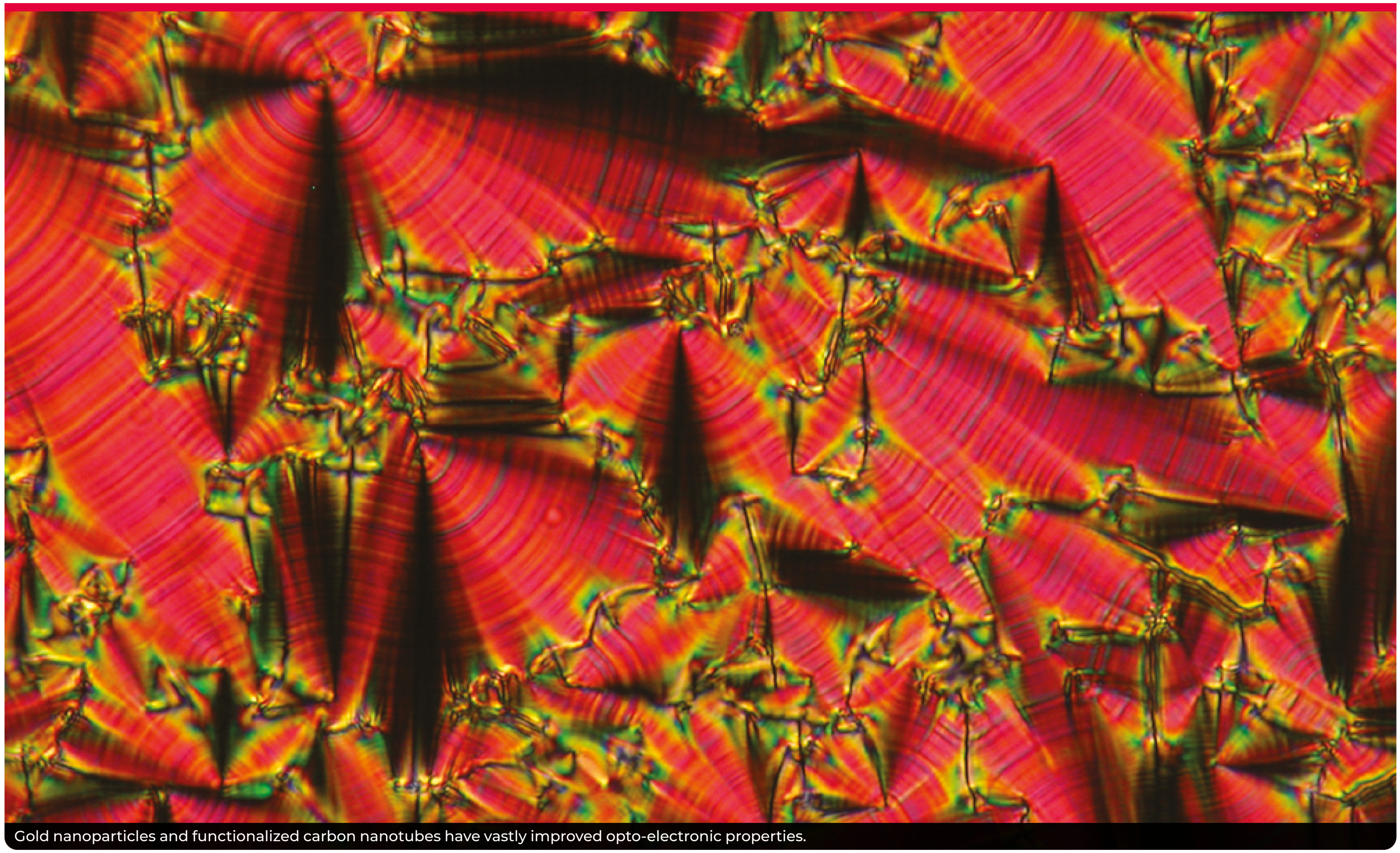
Ground-breaking discoveries in liquid crystals

The discovery of discoid liquid crystals in the 1970s has paved the way for a new generation of organic electronics

K A Suresh



Gold nanoparticles and functionalized carbon nanotubes have vastly improved opto-electronic properties.

KATERYNA KON/ SHUTTERSTOCK.COM

Liquid crystal (LC) phase is an intermediate phase between a solid and a liquid phase. Liquid crystals generally have rod-like molecules, but in the 1970s there were attempts to find out whether disc-like molecules, being anisotropic in shape, can exhibit a liquid crystal phase.

The project was taken up by Sivaramakrishna Chandrasekhar in the 1970s who was then the head of the Liquid Crystal Laboratory at the Raman Research Institute (RRI). Chemistry professor Ganugapati Sree Rama Subba Rao at the Indian Institute of Science suggested a few molecules for synthesis including benzene-hexa-n-alkanoates(BHAs). At the beginning of 1976, the synthesis was taken up by Shyam Singh who joined RRI as a scientist after his postdoc in the UK. Since Kattera Appanna Suresh had worked and gained expertise in optics, thermodynamics, texture studies and X-ray diffraction, Chandrasekhar assigned him to study Singh's BHA samples. Suresh found the samples to be somewhat impure although they did exhibit an LC phase.Singh was trying to purify them, but had to put this on pause to take a month's leave for his sister's wedding. Chandrasekhar became impatient and asked Bookinkere Kapanipathaiya Sadashiva, then a PhD student, to continue Singh's work. Sadashiva prepared pure samples of BHA. Texture and thermodynamic studies of Suresh found they exhibited the LC phase.

> *"This opened up an entirely new branch in the field of liquid crystals, discotic liquid crystals (DLC)." Hundreds of papers followed."*

Suresh took X-rays to investigate the structure of BHA in the LC phase. The powder diffraction patterns at room temperature showed features of a crystalline phase which on heating to LC phase exhibited smectic-like features. After much experimentation, Suresh was able to get an X-ray of an aligned sample that showed a hexagonal symmetry which appeared to be more like a crystalline phase. Chandrasekhar thought that the sample had crystallized and was not in LC phase. Suresh repeated the X-rays many times and consistently obtained pictures showing hexagonal symmetry. He was convinced that it was a picture of BHA in the LC phase. He proposed a model of the discs stacked one on top of the other in columns which constitute a hexagonal columnar structure.

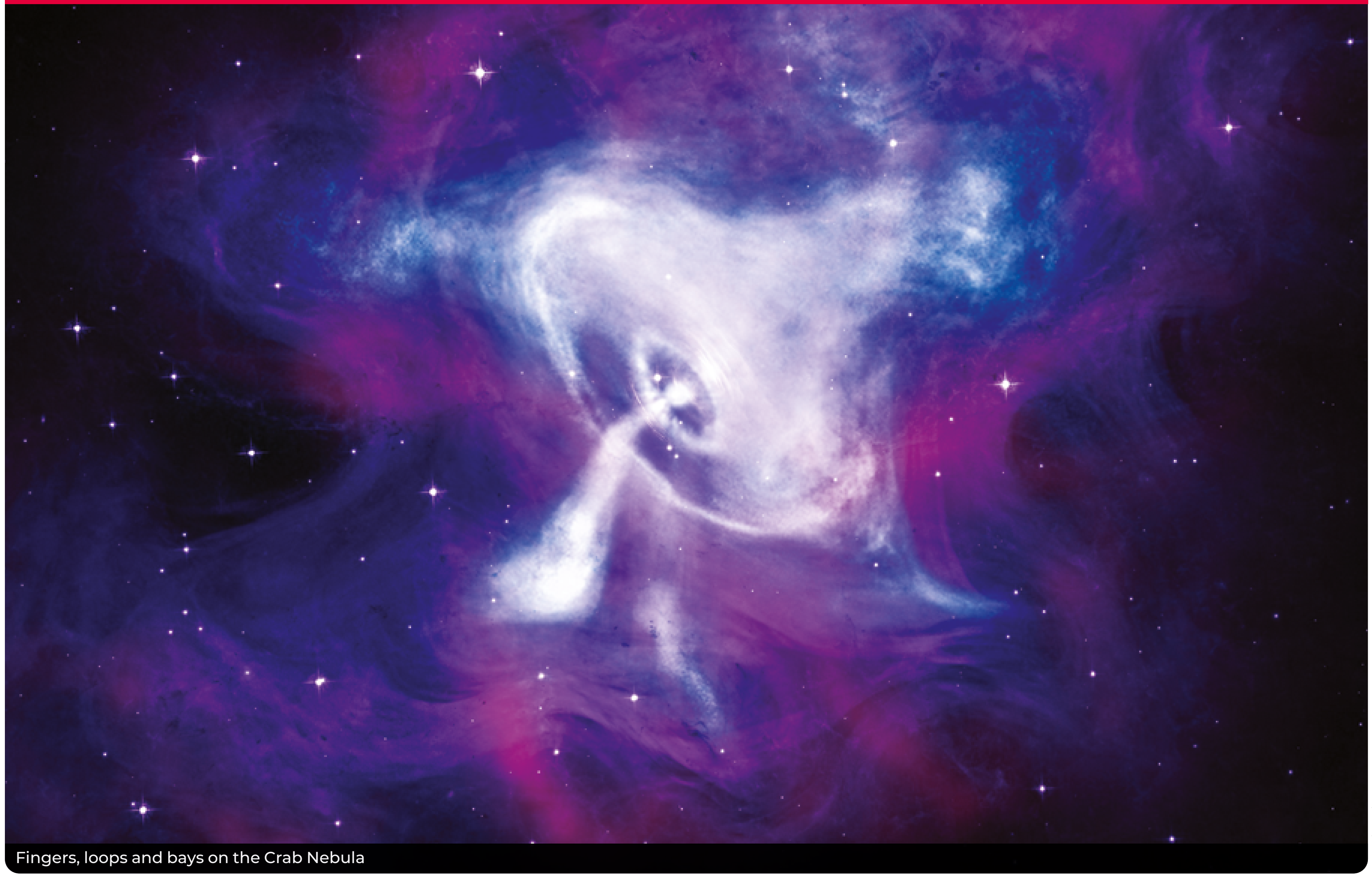
In the meantime, Gobbalipur Shamanna Ranganath came up with a theoretical model consisting of sheets, each sheet containing a hexagonal close-packed arrangement of discs. After much deliberation, it was agreed that the X-ray investigations supported Suresh's model of hexagonal columnar structure, but Ranganath's model was also stated in the paper as a possibility. After the publication of the findings, the scientific community accepted the model of hexagonal columnar structure with a two dimensional hexagonal order and a liquid-like order in the third dimension as the correct representation of the discotic columnar LC phase.

The paper turned out to be the first report of a thermotropic liquid crystal phase formed with a pure, single component system of disc-like molecules. This opened up an entirely new branch in the field of liquid crystals, namely, discotic liquid crystals (DLC). Hundreds of papers followed, reporting on the synthesis of numerous discotic molecules and their physical properties. Many variants of the discotic columnar phase were found. They have been classified into hexagonal, columnar, rectangular columnar, helical columnar, tetragonal columnar and tilted columnar phases. Most of the DLCs are formed by molecules with aromatic cores. They tend to form the columnar phase due to π-π interactions of the aromatic cores.The aromatic cores facilitate charge transfer along the stacking direction. The DLCs have been used as materials for a new generation of organic electronics, as one-dimensional electrical conductors, materials for organic light emitting diodes, discotic photovoltaic devices, discotic field effect transistors and discotic solar cells.

In addition to columnar phases, it has been found that disc-like molecules can form a discotic nematic (DN) phase. DN phase consists of discotic molecules oriented about their disc's normal axis or short molecular axis. The molecules possess translational and rotational freedom about their disc's normal axis.

In the DN phase, the discotic molecules have orientational order but no long-range translational order. Many materials have been synthesized which exhibit DN phase at room temperature. This has paved the way to create new display devices. These displays show significant improvement relating to wide and symmetrical viewing angle profile compared with conventional LC displays.

Doping of nanoparticles (NPs) in DLCs has become a fast developing area of research. These DLC-NPs hybrid systems have potential for significantly improving electronic devices. In a simple procedure, a small amount of functionalized NPs are dispersed in different DLCs. For example, hexanethiol-coated gold NPs, hexadecylamine-coated gold NPs and functionalized carbon nanotubes have markedly improved opto-electronic properties. ■



Fingers, loops and bays on the Crab Nebula

NASA/CXC/SAO

Reincarnation of pulsars

The evolution of a theory that originated at the Raman Research Institute in the 1980s and was emphatically proven 40 years later

Ganesan Srinivasan

In the paper ‘On the origin of the recently discovered ultra-rapid pulsar’ (*Curr. Sci.* **51**; 1096-99; 1982) Venkatraman Radhakrishnan and I argued that the then recently discovered ‘solitary’ millisecond pulsar must have been born in a low-mass X-ray binary system (LMXB) and spun up to an ultrashort period during mass accretion from a companion. In other words, although the pulsar was solitary when it was observed, it must have been a ‘recycled’ pulsar from an LMXB. Using this hypothesis, we predicted that the magnetic field of the pulsar must be 5x10^{8} G and this was confirmed by observations a few months later.

The scenario for resurrecting a pulsar from its graveyard was first advanced in an earlier publication from the Raman Research Institute (RRI) (G. Srinivasan and E.P.J. van den Heuvel *Astron. Astrophys*. **108**, 143–147; 1982) while discussing the Hulse-Taylor pulsar. The pulsar had anomalous properties: its rapid spin rate suggested that it might be ‘young’, while its low magnetic field suggested that it might be a ‘very old’ star whose field had mysteriously decayed. The Hulse-Taylor pulsar was identified as the ‘first-born’ of the two neutron stars, the one that had been spun up, while the other unseen neutron star must be the ‘second-born’ and would have ‘normal’ properties similar to the Crab pulsar. The discovery of the double pulsar system in 2003 confirmed this prediction.

> *“To this day, this is the only plausible proposed mechanism for field decay.”*

The discovery of a second millisecond pulsar further confirmed the recycling hypothesis. This one was in a binary system with a low-mass white dwarf companion as would be expected if the progenitors of millisecond pulsars were LMXBs. In a subsequent paper by researchers at RRI (D. Bhattacharya and G. Srinivasan *Curr. Sci.* **55**, 327–330; 1986) this idea was pursued further and several bold predictions were made including that:

- Most millisecond pulsars will be in binaries with low-mass white dwarfs as companions;
- There must be a very large population of these pulsars;
- Their magnetic fields will be close to 5x10^{8} G.

Although the recycling scenario quantitatively explained the properties of the Hulse-Taylor pulsar, it was not accepted for a long time, based on two objections:

- If the pulsar was ‘spun up’ to its presently observed ultra-short period, then why didn’t we see pulsating X-ray sources with such short periods?
- There was no plausible mechanism for the decay of magnetic fields of neutron stars.

For a neutron star to spin up to a short period, its magnetic field must be many orders of magnitude smaller than that of most pulsars. The low fields of recycled pulsars must somehow be the result of decay during the binary evolution. The difficulty was that in theory, it was not expected that the field would decay significantly even over cosmological timescales and there was no plausible connection between binary evolution and field decay.

A paper published by researchers at the RRI in 1990 provided the breakthrough (G. Srinivasan et al. *Curr. Sci.* **59,** 1, 31–38; 1990). Before the discovery of neutron stars, Russian physicists had given compelling arguments for superconducting and superfluid states in the interior of neutron stars. Because the neutron star has a magnetic field and is rotating, both the proton superconductor and the neutron superfluid will be in a quantised vortex state. The novel mechanism for field decay discussed in the paper involved the interpinning of the quantised vortices in the proton superconductor and the quantised neutron vortices. As the first-born neutron star spun down because of the electromagnetic torque exerted by the stellar wind from the companion, the neutron vortices migrated towards the crust and in the process dragged the magnetic vortices with them. The field then decayed in the crust due to ohmic dissipation. To this day, this is the only plausible proposed mechanism for field decay.

One of the predictions made was that there must be two classes of recycled pulsars – those from massive binaries with magnetic fields of about 10^{10} G and those from low-mass binaries with fields of about 5x10^{8} G. Today, more than 2,000 pulsars have been discovered. The overwhelming majority of them are solitary and have magnetic fields in the range of 10^{12} to 10^{14} G. They form a compact island in the magnetic field-period plane. There are two distinct populations of pulsars with binary companions well beyond this island of pulsars. Those whose progenitors were massive binaries – including the Hulse-Taylor pulsar – have fields of about 10^{10} G. The second distinct population consists of more than 100 millisecond pulsars, most of them in binaries with low-mass white dwarf companions. Their magnetic fields cluster in a narrow range of around 5x10^{8} G. Thus, the predictions made 40 years ago have been confirmed.

As mentioned above, one of the sustained objections to the recycling theory was the absence of evidence of rapidly spinning neutron stars in accreting X-ray binaries, which would provide definitive proof of the spin-up hypothesis. Dramatic evidence came in 2014 when several transient millisecond pulsars were discovered. Some LMXBs switched off now and then, revealing millisecond radio pulsars during the X-ray quiet phase. The smoking gun had been found.

There was one other prediction made by astronomers at RRI concerning millisecond pulsars. In 1988, when only three millisecond pulsars had been discovered, Srinivasan predicted that millisecond pulsars will be strong sources of gamma rays and, since a very large population of millisecond pulsars is expected to exist in our galaxy, there should a large population of millisecond pulsars that emit gamma rays (G. Srinivasan *Adv. Space. Res.* **10,** 2, 167–178; 1990). More than 20 years after the prediction was made, the Fermi Gamma-Ray Space Telescope discovered over 100 gamma ray emitting millisecond pulsars all with fields of around 5x10^{8} G.

The notion of recycled pulsars was first advanced by RRI astronomers and they identified that the Hulse-Taylor pulsar was one such pulsar. Later, the solitary millisecond pulsar was also identified as a recycled pulsar. They made bold predictions in a series of papers and all of these have now been confirmed by observations. They are part of the many achievements made by researchers at the RRI that are being remembered as it celebrates its platinum jubilee year. ■

75 years of frontier physics

The Raman Research Institute (RRI) is a premier scientific research institute funded by the Indian government's Department of Science and Technology. The institute is focused on fundamental research in frontier areas, revealing wonders of physics over a breathtaking range of scales stretching from the cosmos to the quantum.

The year 2023 marks its 75th year, and the institute celebrated the milestone with six international conferences, launching prestigious named lecture and talk series by eminent scientists from around the world.

Since the institute's founding, scientists and engineers have helmed discoveries in equal measure. The institute's Electronics Engineering Group and Mechanical Engineering Services have built world-class instruments and telescopes in the country and around the globe.

C V Raman: RRI's visionary founder

The renowned physicist, Professor C V Raman, established RRI in Bengaluru in 1948. Raman is known for many noteworthy contributions to the areas of acoustics, scattering of light, crystal dynamics, nature's colours and their perception, among others. He discovered the celebrated Raman effect in 1928, which was awarded the Nobel Prize in Physics in 1930. To commemorate this discovery, and underlying wide ranging applications to science and technology, India celebrates National Science Day on 28 February every year.

Objective and mandate

The research in fundamental sciences covers four main themes.

Astronomy and Astrophysics: *Theoretical astrophysics, observational astronomy, experimental radio and X-Ray astronomy, algorithms and signal processing.*

This group undertakes detailed study of the physical, chemical and dynamic properties of celestial objects and phenomena. RRI has a history of excellence in major space missions, such as AstroSat, the first dedicated Indian astronomy mission studying celestial sources in X-ray, optical and UV spectral bands. It has designed and built POLIX, the first Indian X-ray polarimeter to study high-energy celestial phenomena), to be launched soon on ISRO's XpoSat. The institute is looking forward to PRATUSH, a precision radiometer to be placed in lunar orbit to seek subtle signals from the cosmic dawn from the far side of the moon. Terrestrially, from building the country's first millimetre wave telescope to contributing in the design and development of key electronics, RRI researchers have worked on the Murchison Widefield Array, Ooty Radio Telescope, Mauritius radio telescope, Giant Metrewave Radio Telescope and the Square Kilometre Array – the world's largest proposed radio telescope.

Light and matter physics (LAMP): *Ultracold atoms and molecules, development of quantum-enabled technologies and quantum communications and optics, atom-light interaction and spectroscopy, intense light-matter interactions.*

The group is engaged in research on fundamental properties of electromagnetic (EM) waves and the nature of their interaction with gaseous neutral atoms, ions, condensed matter, and ultracold and exotic states of matter. These studies aim to unravel fundamental processes and provide new guiding principles.

The cluster of quantum labs at RRI has demonstrated frontline achievements, such as secure quantum communication between two stationary sources, and between a stationary and a moving source, developed quantum sensing of magnetic fields at unprecedented sensitivies using neutral atoms at room temperatures, and uncovered novel quantum physics of laser cooled atoms at ultracold temperatures using in-house built apparatus. Another stream of research is on the optical nonlinearity in novel materials and the generation and characterization of laser-produced plasmas.

Soft condensed matter physics (SCM): *Colloids, complex fluids, liquid crystals, nanocomposites, polyelectrolytes, self-assembled systems, polymers and biological materials.*

A fundamental understanding of the structure- property correlations, phase behaviour of these systems, and response to external stimuli form major experiments of the group. The institute has made seminal contributions to the field of liquid crystals, colloids, chemistry, biological processes, properties of soft matter.

The biophysics lab has devised cost-effective instruments for the diagnosis of diseases, including neurological conditions, based on study of force responses of cells and molecules. The rheology labs have developed and investigated smart and adaptive materials, studied earthquakes and behaviours of soft materials to shear jamming effects.

Theoretical physics: *Foundations of quantum mechanics, general relativity, quantum gravity, statistical physics, condensed matter and quantum optics.*

The group has forged robust collaborations with experimental groups within RRI. The connection with the LAMP group is in the areas of precision measurements using atomic systems, foundational questions in quantum mechanics, quantum information and quantum sensing and metrology and non-linear quantum dynamics. The overlap with the SCM group is in areas such as biophysics, polymer physics and modelling stochastic search process. RRI theorists have fruitful ongoing collaborations in all the aforementioned areas within India and elsewhere.

Imparting knowledge

The institute enrols highly motivated students for its PhD programme and offers a vibrant learning space for doctoral studies in the four mandated themes, for experimental or theoretical studies. A comprehensive coursework, research guidance in the aforementioned research areas coupled with exposure to national and international academicians of high standing via conferences, workshops, named lectures and seminars provides the students a holistic approach towards building a career in academics and science.

The institute participates in the Joint Astronomy Programme (JAP) with the Indian Institute of Science along with the Physics and Biology Programme with the National Centre for Biological Sciences. RRI is affiliated to the Jawaharlal Nehru University (JNU), which issues the degrees.

A vibrant two-year post-doctoral programme (extendable by one year) prepares young researchers for independent R&D.

The institute offers specialised training to engineers, and those with a Master's degree in science or relevant subjects through the Research Assistantship programme. Students working alongside experienced scientists and engineers are engaged in multi-institutional missions and projects.

The Visiting Student Programme, applications for which are open throughout the year, is for students who are either in their gap year or pursuing undergraduate or post-graduate degrees.

Communicating knowledge

Apart from generating high end research manpower, the institute engages with school, college and university-level students and the general public via a number of science outreach activities for greater engagement and dissemination of its research.

RRI has nurtured a healthy balance of top-end scientific research, together with technological capability that holds great promise for future frontier endeavours at par with the best in the world. RRI plans to leverage the unique role that it can play both within the S&T ecosystem in the national and international arena.

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CELEBRATING 75 YEARS OF SCIENTIFIC EXCELLENCE

Self-assembling nanocarriers for drug delivery

Research that is helping to bring drugs straight to their target

Ranjini Bandyopadhyay

Soft materials are constituted by weakly interacting macromolecules that are easily deformed by thermal stresses at room temperature. Some examples of common soft materials include: colloidal suspensions, such as ink and paint; detergents; emulsions, such as mayonnaise and butter; gels; foams; and pastes. Even though these materials appear to be disparate, Pierre-Gilles de Gennes, the winner of the Nobel Prize for physics in 1991, pointed out that all soft materials possess structural complexity and mechanical flexibility. These features result in intriguing behaviours such as spontaneous self-assembly of macromolecules into fragile structures and thinning and thickening of viscosity under shear.

Colloidal suspensions comprise microscopic particles that stay uniformly distributed in a continuous medium due to their incessant temperature-induced jiggling (known as Brownian motion). Granular suspensions, in comparison, are constituted of larger 'non-Brownian' particles. Since 2005, researchers at the Rheology and Light Scattering (RheoDLS) lab at the Raman Research Institute have studied the following aspects of soft materials through experimental techniques: modelling suspensions as scaled-up versions of atomic matter; setting up laboratory experiments to mimic geophysical phenomena such as landslides and river delta formation; and implementing table-top experiments to study non-equilibrium flows and pattern formation. Research emerging from the lab can be used in therapeutic, industrial and personal care applications.

The science of soft materials is strongly rooted in interdisciplinary ideas and employs concepts of physics, chemistry and biology to design and understand complex materials. Soft materials such as liposomes and polymer-based micelles have been shown to be efficient vehicles for the transport of therapeutic agents such as drugs and genes. Drugs packaged within the cores of nano-sized 'soft' micellar capsules can even be delivered to specific targets (E.V. Batrakova and A.V. Kabanov, *J. Control. Release* **130,** 98; 2008).

Rajib Basak, a former member of the RheoDLS lab, and Ranjini Bandyopadhyay, principal investigator, explored the use of self-assembled micellar systems of colloidal sizes as biocompatible nanocarriers for drug molecules in a study published in 2013 (*Langmuir* **29,** 13, 4350–4356; 2013). They encapsulated painkilling and antibiotic drugs — aspirin, ibuprofen and erythromycin — in spherical micelles formed by triblock copolymer Pluronic macromolecules at room temperature.

Pluronic is amphiphilic — this means that each Pluronic macromolecule possesses water-loving (hydrophilic) and water-hating (hydrophobic) portions. While the two-sided blocks of polyethylene oxide (PEO) are hydrophilic, the polypropylene oxide (PPO) block in the middle remains hydrophobic over a large temperature range. At high enough temperatures, the central PPO block becomes very hydrophobic and the PEO chains dehydrate significantly. This drives the association of Pluronic macromolecules into spherical micelles with hydrophobic PPO cores and hydrophilic PEO coronas. Since drug molecules are hydrophobic, they solubilise easily within the micellar cores. Basak and Bandyopadhyay's research systematically assessed the properties of the individual drug-encapsulated micellar nanocarriers and demonstrated that environmental temperature and solution pH serve as efficient knobs to control the uptake of drugs in Pluronic micelles and their subsequent release and delivery.

Lipid-coated polymeric nanoparticles for drug delivery.

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Electron micrographs of individual Pluronic micelles showed globular shapes and sizes of 60–70 nm. The micelles remained globular though their sizes increased when drug molecules were incorporated in the micellar cores. Dynamic light scattering experiments verified these results and revealed a decrease in the critical micellisation temperature (CMT) in the presence of drugs. Below the CMT, the micellar nanocarriers decompose into individual amphiphilic molecules and deliver the encapsulated drugs.

> *"Soft materials such as liposomes and polymer-based micelles are shown to be efficient vehicles."*

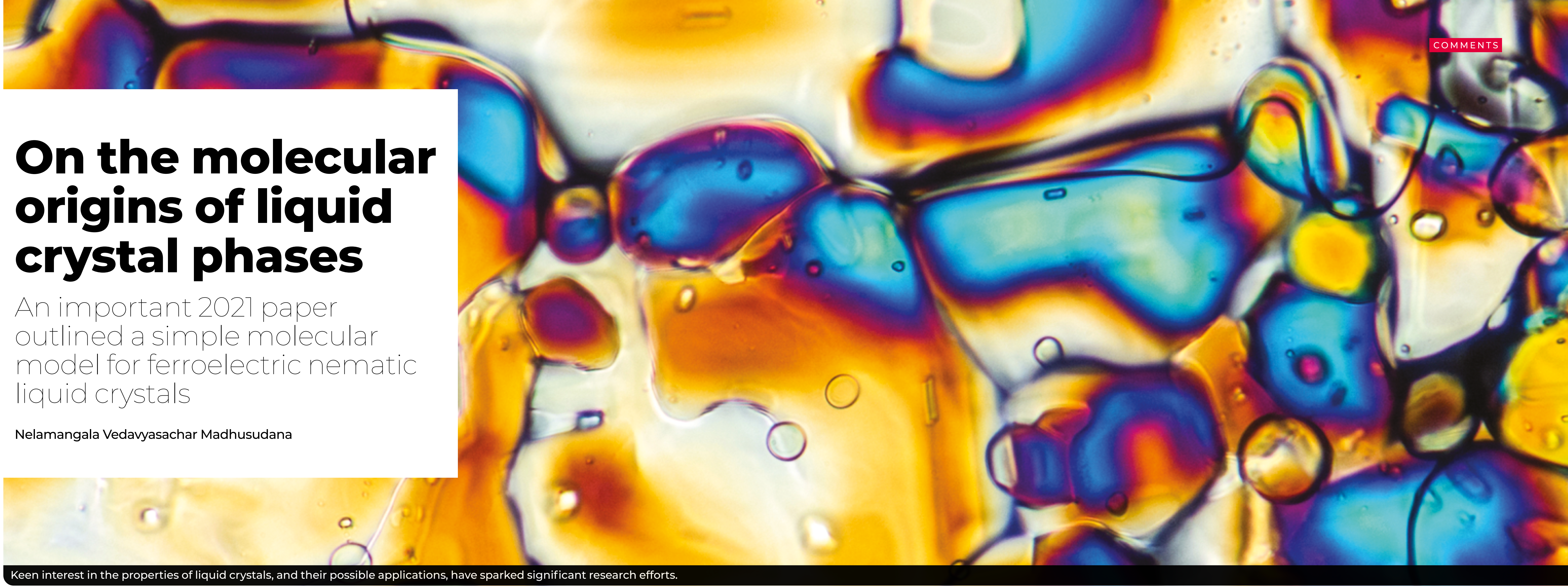
Fluorescence measurements with aromatic pyrene probe molecules pointed to enhanced water penetration in the micellar cores with decreasing temperature. This work suggested two strategies for releasing drugs inside micellar nanocarriers – by decreasing the temperature below 15ºC or by increasing the pH of the solution medium. Cooling the target site or releasing an agent to marginally increase the pH at the target can therefore trigger drug delivery.

Incorporating drugs in the hydrophobic cores of Pluronic micelles enhances the former's solubility and circulation times. The nanocarriers synthesised in the Basak and Bandyopadhyay study can be sterilised using standard filtration methods and delivered into the bloodstream using intravenous injection. The study by Batrakova and Kabanov reported that drug-encapsulated Pluronic nanocarriers can be delivered across the blood-brain and intestinal barriers, and toxicity studies showed that Pluronic has low in vivo toxicity and can be safely used in human subjects at low concentrations (R.M. Ottenbrite and R. Javan. in *Encyclopedia of Condensed Matter Physics*; 2005). A Pluronic-based platform for drug delivery therefore holds enormous promise in the field of nanomedicine. ■

On the molecular origins of liquid crystal phases

An important 2021 paper outlined a simple molecular model for ferroelectric nematic liquid crystals

Nelamangala Vedavyasachar Madhusudana



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Keen interest in the properties of liquid crystals, and their possible applications, have sparked significant research efforts.

Thermotropic liquid crystals (LC) are exhibited by many organic molecules and they all have shape anisotropy[1]. Nematic LCs (NLC) having a pure orientational order of rod-like molecules and were first identified more than 130 years ago. Max Born proposed the first molecular theory for the order in 1916[2], when he suggested that the medium is a ferroelectric liquid with the order resulting from dipolar interactions. Later, it was established that the nematic-isotropic transition point depends on anisotropic dispersion interactions[1] and the order is apolar in nature.

The operating voltage of liquid crystal displays can be brought down by increasing the dielectric anisotropy of NLC, usually by attaching the highly polar -C≡N or -NO$_2$ end groups to the molecules. The electrostatic interaction energy of neighbouring polar molecules is lowered by a mutually antiparallel orientation, with the nematic retaining the apolar order[3]. X-ray studies showed that the strong dispersion interaction leads to a short-range order with a partial bilayer structure with spacing around 1.4 times the molecular length as the chains of neighbours are also thrown apart in opposite directions[1]. Later, several compounds were found to exhibit the sequence Iso-N-SmA$_d$-N$_{re}$-SmA$_1$ as the temperature is lowered; the reentrant nematic N$_{re}$ and reentrant SmA$_1$ with a layer spacing equal to the molecular length occurring at temperatures lower than that of the partial bilayer smectic SmA$_d$ phase[1].

Jacques Prost developed a phenomenological Landau theory[4] showing that frustration between the order parameters corresponding to the two layer-spacings leads to the above sequence of phases. The molecular origin of the two spacings is traced by noting that in the SmA$_d$ phase the chains are thrown apart and do not have a significant interaction. The dispersion interaction between the chains is favourable if the two neighbouring molecules are parallel. The repulsive dipolar interaction is mitigated by the effect of the dipole induced in the aromatic core of a given molecule by the dipole of the neighbour, which reduces the net dipole moment. As both dispersion energy and dipole-induced dipole energy favouring the parallel orientation are proportional to r^{-6}, where r is the intermolecular separation and the repulsive dipole-dipole interaction to r^{-3}, when the molecules come closer at lower temperatures, the observed sequence is the result[5]. In some favourable cases, a nematic-nematic transition was also predicted[6], with a relative jump in the two types of short-range order, which has been seen in some experiments[7]. There have been a number of theoretical and computer simulation studies looking for the ferronematic (Nf) phase in small, highly polar molecules[8], but only polar discs were found to favour the Nf phase.

In 2017, two very different types of compounds with highly polar rod-like molecules were synthesised[9,10], which were shown to form the Nf phase[10,11] with a polarisation of ~6-8 $\mu C/cm^2$, which is about an order of magnitude larger than that shown by some types of smectic liquid crystals in the plane of the layers[1,12]. Remarkably, at the isotropic to nematic transition temperature, the nematic phase is of the usual type, with an antiparallel short-range order and an apolar long-range order. As it is cooled to a specific temperature, there is a transition to the Nf phase with a long-range polar order.

The intrinsic interest in the physical properties of a liquid with polar order – and its possible applications – have triggered intensive research activity on the topic. Over 200 new compounds exhibiting the Nf phase have been synthesised. Again, a fundamental question concerns the molecular origin of the Nf phase and an idealised generic model has been proposed. Each molecule is assumed to be a cylindrical rod with four surface charge density waves[3]. Detailed calculations have been used to show that near neighbour rods favour antiparallel orientation for a moderate inter-rod separation r, which switches over to parallel orientation below some r, only if the waves of charge density at the end half have lower amplitudes than those of the interior waves[13]. This is borne out by the structures of the molecules synthesised so far[14]. For example, in many compounds exhibiting the Nf phase, the polar group at one end is -NO$_2$, the nitrogen atom effectively reducing the negative charges of the oxygen atoms projecting out towards the sides of the molecules. If this group is replaced by the equally polar -C≡N group, this structure is lost and the compound exhibits only the nematic (N) phase with antiparallel short-range order, which does not go over to the Nf phase[9].

The basic physical mechanism for the stability of the Nf phase is the following: when the neighbouring molecules are very close, they can sense the detailed charge distributions from their neighbour. The lowered charge densities of the end half waves reduces the interaction energy of antiparallel rods with full overlap and increases the attractive energy of parallel molecules having the favoured structure with a shift by half a wavelength along the length. The proposed mechanism and experimental observations show that the orientational order of the N phase does not arise from dipolar interactions as proposed by Max Born[2], but by the usual anisotropic dispersion interactions. The Nf phase is seen only in some compounds with special charge structures when the density is high enough[13,14]. Interestingly, the ferroelectric SmAf phase in which the polarisation is along the normal layer has been discovered only recently[15]. Work carried out at the Raman Research Institute has clarified the molecular origins of all the unusual LC phases shown by polar molecules. ■

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Large liquid crystal display devices at Mumbai airport.

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Exploring the properties of bent-core liquid crystals

Tom Lubensky's 'new banana phases'

Pratibha Ramarao and Nelamangala Vedavyasachar Madhusudana

Anisotropy of molecular shape is essential for the formation of thermotropic liquid crystals (LCs)[1]. Rod-like mesogens have been known for well over a century and disc-like mesogens were identified in 1977. They have an essentially uniaxial shape and the nematic phase exhibited by many of them also has uniaxial symmetry with an apolar orientational order along a line. Several theories suggested the possibility of the formation of the biaxial nematic phase (with three orthogonal directions with apolar order) in mixtures of the two types of molecules[1], though only a coexistence of the two types of nematic was found, with interesting defect structures[2].

Bent core (BC) molecules – also popularly known as banana-shaped molecules – are intrinsically biaxial with shape polarity and they exhibit unusual types of LCs, mainly forming layers with a polar order[3]. An intensive international effort to synthesise and study the physical properties of compounds with BC molecules with different core structures began in the late 1990s in many laboratories, and in particular by Bookinkere Kapanipathaiya Sadashiva at the Raman Research Institute (RRI). Rod-like mesogens usually have aromatic cores with large polarisability, attached with aliphatic chains with low polarisability, leading to a nano-segregation between the two moieties and the formation of smectic LCs with layered structures[1]. As BC molecules are just bent rods, long chains give rise to the layered B_2 phases with tilted molecules[3].

Mixing mesogens with the two types of molecules is of obvious interest, but if the dimensions of the cores and chains of the two components match, only a simple intermediate structure is exhibited by the mixture[3]. Sadashiva had also synthesised some rod-like mesogens with a chain at only one end of the rod, resulting in a bilayer SmA_2 phase. When this was mixed with a compound with BC molecules exhibiting the B_2 phase, the resulting phase diagram was quite unexpected[4]. At low concentrations of the rod-like molecules, the latter just fit in with the B_2 layers. Beyond ~16 mole%, the rods break up the layers and the B_1 phase with a 2D rectangular lattice is found, the rods acting as glue between the broken layers. When the concentration of rod-like molecules exceeds ~62%, the break-up is complete, giving rise to the B_6 phase in which the rods stitch the aromatic cores of the BC molecules so that the latter intercalate to form layers with a spacing which is only half the molecular length. Interestingly, the B_1 and B_6 phases are exhibited as the chain length is decreased in the pure compound with BC molecules.

> **"Mixing mesogens with the two types of molecules is of obvious interest."**

The most interesting part of the phase diagram occurs when the concentration of rod-like molecules exceeds ~86%. In this rod-rich region, the bilayers of the SmA_2 phase have to accommodate the BC molecules and the biphilic nature of both types of molecules forces the long axes of the BC molecules to orient in a direction perpendicular to the layer-normal. At higher temperatures, the long axes of BC molecules are orientationally disordered in the layers and the SmA_2 phase has uniaxial symmetry. As the temperature is lowered to some concentration-dependent value, the long axes develop an orientational order and the medium becomes the biaxial SmA_{2b} phase, as established by the nature of the defects exhibited by the medium[4].

Later, the compound with rod-like molecules was replaced by another one which also had the chain attached only at one end. This produced an essentially similar phase diagram, and polarised infrared spectroscopy was used to establish the relative orientations between the two types of molecules in different phases[5]. Subsequent simulations on mixtures of hard rods and hard BC rods found only the $SmAP_{AF}$ phase with an antiferroelectric order of the polarisation of successive layers[3], bringing out the essential role of biphilicity of the two types of molecules for the experimentally observed mutual orientations, as noted in the perspective by Tom Lubensky[6]. The SmA_{AF} phase has been found in pure BC compounds at the Raman Research Institute[7] and elsewhere[3]. The macroscopic symmetry of this structure is also that of SmA_b although the low frequency electric field response arises from polar interaction, rather than the apolar interaction as in the SmA_{2b} phase. The rod-rich mixtures also exhibit the uniaxial nematic phase as the SmA_2 phase is heated above its transition temperature. The elasticity to resist bend distortion of the orientational field of the nematic was found to decrease as the temperature was lowered in the nematic, even though the orientational order parameter increased[8]. The anomalous trend arises from a stronger coupling of the distortion with the bent shape of the BC molecules at lower temperatures. Later, a similar trend was found in nematics made of pure BC molecules[3].

The results reported in 2000[4] required careful molecular engineering of the two types of molecules and in fact most other studies on other mixtures have not found the occurrence of new phases[3]. The results also triggered an effort to find the SmA_b phase – mainly of the type $SmAP_{AF}$ – in pure compounds made of BC molecules[3], and to find interesting electro-optic responses. The strong reduction of the bend elastic constant of the nematic with BC molecules also leads to a sharper electro-optic response in such materials[8], which can be useful for large liquid crystal display devices. ■

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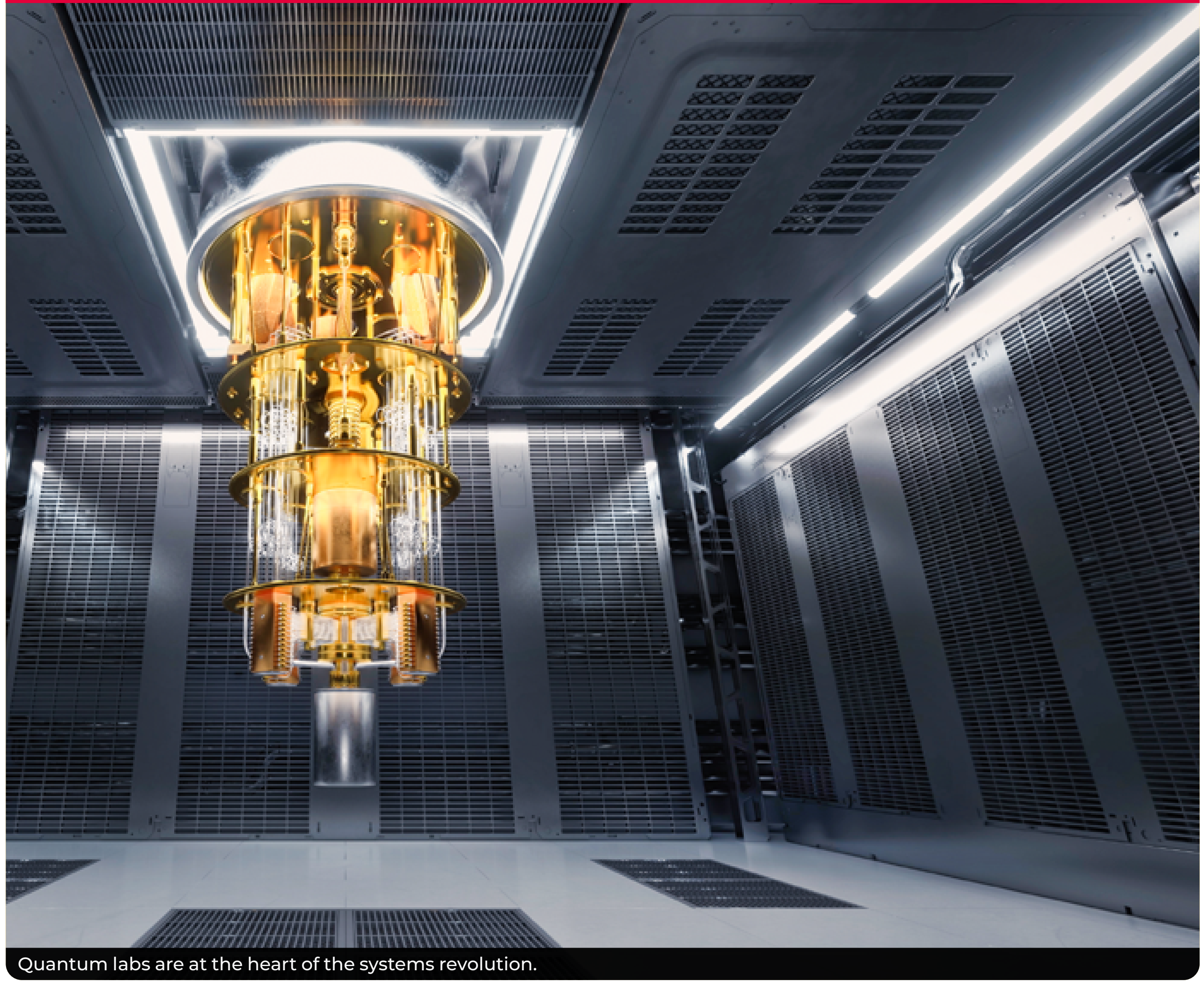
Cooling by quantum pickpocketing

The discovery of dual cooling mechanisms in a mixed ion –atom system

Sadiq Rangwala



Quantum labs are at the heart of the systems revolution.

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Quantum physics and its application has dominated the description of physical phenomena since the beginning of the twentieth century. Central to these developments has been the detailed studies of atomic and molecular systems and their ions. In the last decades of the twentieth century, the ability to trap and cool single or few atoms/ions/molecules in a dilute gas ensemble allowed the opportunity to repeatedly interrogate particle quantum systems with unprecedented precision.

Trapping

The trapping of an atom (A), molecule (M) or their ions (I) is accomplished by specifically tailored configurations of electric, magnetic and optical fields. Traps are isolated regions of space where the displaced particle feels a restoring force towards the trap centre. Traps are formed over very small volumes in space – ~ mm^3 or less in most cases – and have a maximum potential energy (PE) for particle confinement. When the kinetic energy of the trapped particle exceeds the maximum trap PE, the particle escapes the trap. To keep the particle continuously trapped, cooling of the trapped particles is necessary to bleed away the kinetic energy gained by the particle via uncontrolled fluctuations, imperfections as well as in the act of measurement.

Cooling

Cooling of quantum systems reduces the motional energy spread and requires the removal of kinetic energy from the motion of the particle. It is mediated by interactions that are inherently dissipative or inelastic and is achieved via a scattering process with fields, such as light, or material particles, such as atoms. Trapping, cooling and manipulation of single species of particle have led to tremendous advances in the fields of precision spectroscopy and metrology, quantum many-body physics and more.

Experimental background

In the mid-2000s, my colleagues at the Raman Research Institute (RRI) K. Ravi, Arijit Sharma and I started thinking about studying interactions at the quantum limit. Previous studies were doing a wonderful job of investigating particle-particle interaction with single trapped species, such as atoms or ions. Our aim was to study interspecies interactions between atoms and ions in the quantum regime when they were both trapped and cooled. This would allow us to look at a far wider range of interactions and enable the study of interacting quantum systems, which is fascinating and relevant to the quantum revolution we are in now.

Hybrid traps

We came up with the concept of hybrid traps (as they are now known), which combine the possibilities of simultaneously cooling and trapping distinct species such as atoms, ions and molecules in overlapping traps. Hybrid traps allow the preparation of both the internal states and the motional states of the two species, so that the interaction of interest can be studied with high precision and specificity. In what follows we will refer to the scientific knowledge of the time when we studied the interactions between trapped ions and laser-cooled atoms, rather than what has been discovered since.

Our first hybrid trap was a combined linear Paul trap with a magneto-optical trap (MOT). A Paul trap combines radio frequency voltages on electrodes with DC voltages. The time varying fields dynamically trap ions as static electric fields cannot make an ion trap as explained by Earnshaw's theorem. The MOT combines laser cooling with gradient magnetic fields to achieve spatially localised cooling and trapping of atoms. In the years that have followed, more versatile hybrid traps have been built at RRI.

Tension with established thought

We first created an MOT of atoms and then ionised a small fraction of laser-cooled rubidium (Rb) atoms using two-photon ionisation. Since the ions were created in the overlapped trap centre of the two traps and the laser-cooled atoms had very low kinetic energy, the daughter ions created by ionisation were trapped in the ion trap. The trapped Rb+ ions can be detected by extraction to a channel electron multiplier (CEM) and identified by the time of flight taken. How long the trapped ions survive in the ion trap is then determined by measuring the loss of ions as a function of trap hold times. The cooling of the ions was determined by the application of the virial theorem to the widths of the time of flight distribution of the extracted ions. The longer the ions are held in the trap, the more efficient the ion cooling is in combatting the heating of the ions from all the uncontrolled processes. The Rb$^+$ ion cannot be laser-cooled as the lowest optical transition is deep in the vacuum ultraviolet regime. The only cooling mechanism available to the Rb+ ion is collisions with the trapped Rb atoms.

We observed very efficient collisional cooling of the ions (Ravi, K., Lee, S., *et al. Nat Commun* **3**, 1126; 2012). This was totally unexpected according to the foundational paper on collisional cooling of trapped ions by Fouad Major and Hans Dehmelt (*Phys. Rev.* 170, 91; 1968). Simply put, their theory, which a number of experiments had verified, predicted that for equal mass of ion (m_I) and atoms (m_A) no net heating or cooling could occur. To cool an ion efficiently by collisions, the condition was $m_A<m_I$ (more practically $m_A \ll m_I$) and the condition $m_A>m_I$ would lead to rapid heating of the ion. Our experimental measurements for which strong cooling was observed was for $m_A=m_I$, firmly contradicting the long established paradigm.

Two cooling mechanisms

We showed how cooling by elastic collisions worked quite differently when the coolant atoms were spatially compact and centred at the bottom of the ion trap. However, the observed ion lifetime data suggested there had been highly efficient cooling that had been far greater than could be supported by elastic collisions, since the large majority of collisions would be glancing which, on average, would result in very little momentum transfer. This signalled the presence of another much more effective cooling process. We proposed that the cooling was mediated by resonant charge exchange (RCE). In this mechanism, when the cold parent atom collides with a fast daughter ion without any change in internal energy an electron can hop from atom to ion resulting in a cold ion and a fast atom after the collision. Such an exchange of kinetic state of the ion and atom, resulting from the hop of a single electron from one ion core to an identical core makes resonant charge exchange an effective cooling mechanism. Its exchange-mediated process is quantum in essence and has the light touch of a pickpocket.

Results

To explain the observations, we needed a deep dive into the mechanics of collisional cooling of ions. The trapped ion heats and a collision will reduce its velocity and actually change its post-collision direction, resulting in it shifting from a trapping state to a non-trapping state because the stability of the ion is a function of its velocity vector and the phase of the trap potential. When the direction of the velocity changes after a collision, the ion can become non-trapped and be lost. In our experiment, the collisions happen very close to the bottom of the ion trap where the radiofrequency field is small and therefore the probability of a trap loss collision is very small. So elastic cooling with equal masses works and theory predicts that irrespective of the ratio of masses of the colliding partners, the ions should cool when collisions happen only at the bottom of the ion trap. This was subsequently shown in many theoretical and experimental works.

RCE cooling effects were calculated and its effectiveness in cooling was shown numerically in this study. Subsequent experiments from ours and other groups have confirmed the cooling mechanism. We are now building new experiments at RRI to further investigate this symmetry- and exchange-driven phenomenon.

Conclusion

In summary, in the article we showed unexpected ion cooling and explained it with two different cooling mechanisms and we offered a range of predictions for cooling, which have been subsequently proved. This work was enabled by the invention of a new type of combined trap for ions and atoms, the measurements in which led to an observation that was inconsistent with the canon in the field, encouraging detailed theoretical analysis of collisional cooling and the discovery of the two cooling mechanisms. Needless to say, the key contributions to this and related work in this area at RRI was reliant on the tremendous contributions of K. Ravi, Seunghyun Lee, Arijit Sharma, Tridib Ray, Saraladevi Jyothi, Sourav Dutta, Rahul Sawant and Günter Werth. ■

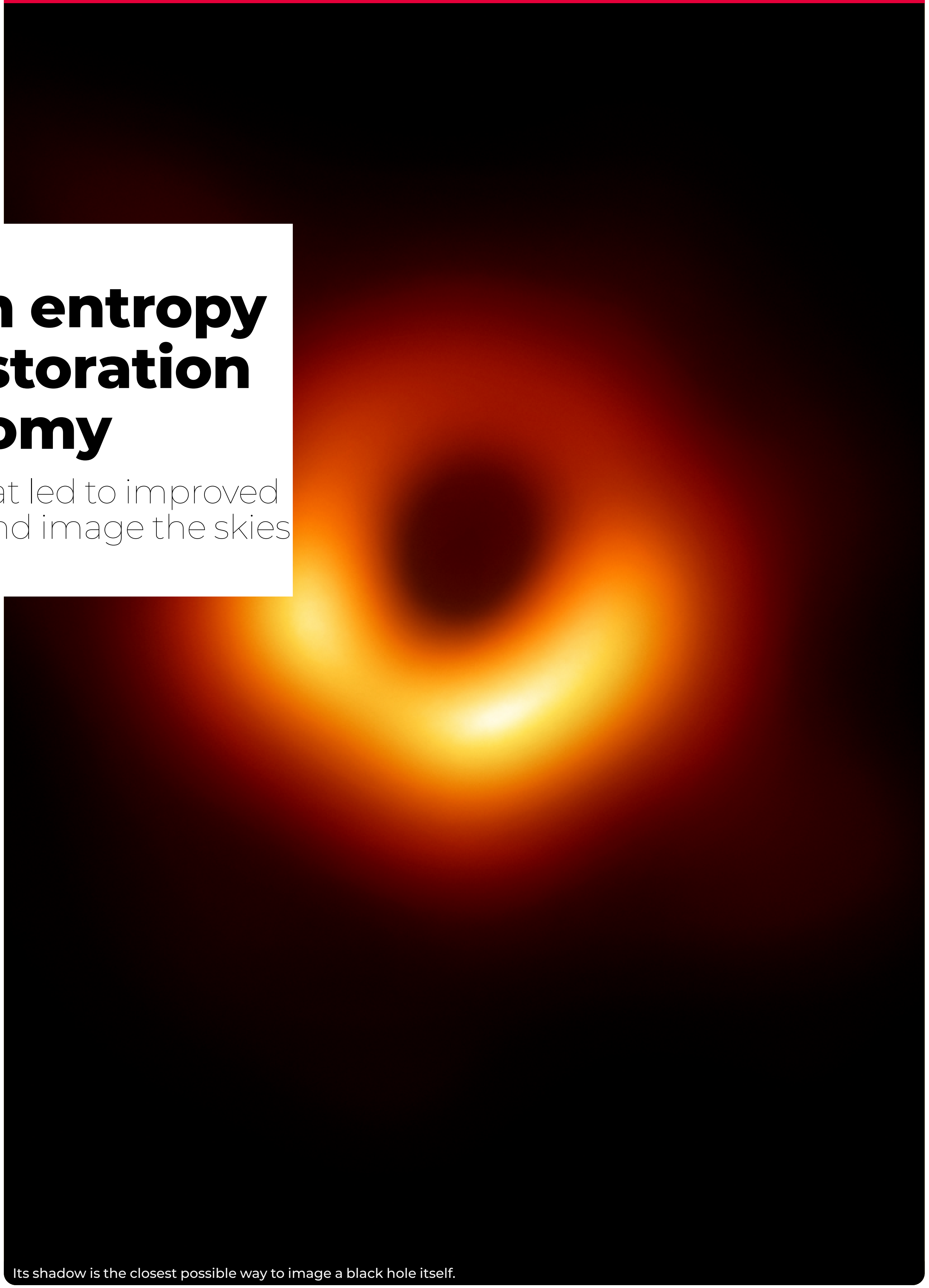
Maximum entropy image restoration in astronomy

Collaborations that led to improved ways to decode and image the skies

Rajaram Nityananda

An individual radio antenna has an angular field of view on the sky– informally known as 'the beam' – which can result in a very poor angular resolution at long wavelengths. Only the combined effect of all the sources in the beam is measured. Martin Ryle won the 1974 Nobel Prize for Physics for a dramatic improvement called 'aperture synthesis' - work that was carried out in Cambridge, UK. Combining the signals from two antennas modifies the response to each source, depending on its position in the beam. It can be enhanced twofold if the path difference is an integer number of wavelengths, or become zero if there is an extra half wavelength. Physically, this is the same effect that Thomas Young used in 1801 to establish the wave nature of light in his famous two-slit experiment.

Mathematically, the sources in the beam are now multiplied by a sine/cosine wave – a series of stripes in the sky. This is nothing but a single measurement of the Fourier transform of the sky brightness. Clearly, many such pairs with different spacings and orientations are needed to build up enough information to unscramble – or deconvolve – all the sources and make an image. Ryle was clear that all the measurements should be made out to a maximum spacing, which defined the angular resolution.



Its shadow is the closest possible way to image a black hole itself.

EHT COLLABORATION

Later, astronomers elsewhere – and even a few in Cambridge – started playing the dangerous game of 'reconstructing' the map of the emission in the sky with fewer measurements.

One such method on the horizon in 1982 was 'maximum entropy' (MEM). The basic idea is that there are many possible maps consistent with a limited set of measurements. The one that is 'most likely' can then be chosen. Thermodynamics tells us that a gas fills a container simply because that is the configuration that can occur in the largest number of ways, as measured by its entropy. This idea was then extended to decoding messages in Claude Shannon's information theory.

The astronomer Jon Ables visited the Raman Research Institute (RRI) from Sydney in 1973 and showed us some startling successes using this approach. He generously shared his code with Rajendra Bhandari, who was intrigued but was also sceptical of reconstruction that almost seemed like resurrection. He soon came up with examples where the MEM did not work that well. It also did not help that the 'entropy' as a function of the intensity in the sky depended on whether you were in Cambridge ($-B \ln B$) or in Sydney ($\ln B$)

Ramesh Narayan came to RRI in 1978 after completing PhD studies at India's National Aerospace Laboratories. He had experience in Fourier transforms. One deconvolution in X-rays was already under his belt. Max Komesaroff was visiting from Sydney at that time and had a new take relating MEM to the positivity constraint. Their collaboration resulted in a much better mathematical understanding of the " $\ln B$ " MEM in one dimension and they shared some of the excitement with me. This triggered further conceptual and computational activity. Ronald Ekers visited later and brought insight into CLEAN – the algorithm of choice at that time for radio maps. Narayan and I began to develop our own codes for CLEAN and MEM in the realistic two dimensional case and tried out different entropy functions. We knew the algebraic form for the reconstruction which the two forms of MEM gave: a nonlinear function, either the reciprocal or the logarithm of a Fourier series. The breakthrough was Narayan's graphical insight that such a nonlinear transformation automatically sharpened peaks and suppressed undesirable baseline ripples.

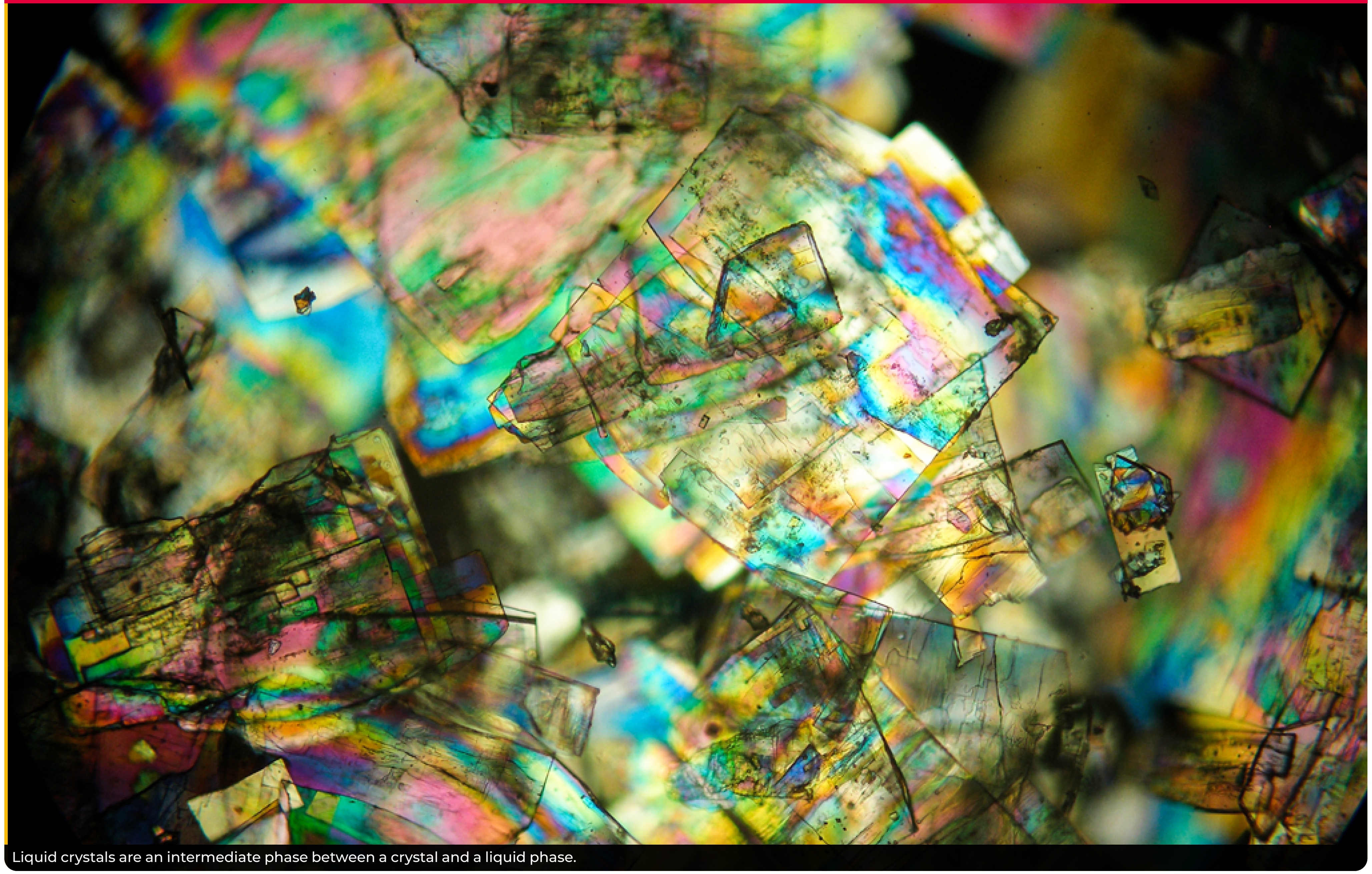
A lot of things fell into place once we were armed with this knowledge, but they had to be backed up with extensive simulations starting with a known image, throwing away some information and seeing if the MEM could recover it. We could understand when it worked and when it didn't and how to control its behaviour. We poured cold water on information theory even in our title – 'a practical non-information-theoretic approach' to the MEM, since we had many more functions which worked just as well. Our paper was published in the newly founded Journal of Astrophysics and Astronomy of the Indian Academy of Sciences (J. Astrophys. Astr. 3, 419–450; 1982).

> ***"A lot of things fell into place once we were armed with this knowledge, but they had to be backed up."***

It helped a great deal that Narayan soon attended a meeting in Sydney on indirect imaging on his way to a fellowship at the California Institute of Technology (Cal Tech). We submitted a generalised version to this conference, including the polarisation of the radio waves. Our pragmatic and practical message won some supporters. In the conference summary, R.H.Bates from New Zealand joked that folk*lore* had N=2 kinds of MEM, but Ban*galore* had pushed N to infinity!

The icing on the cake came when Narayan, now based at Caltech, was invited to cover this area for the prestigious *Annual Reviews of Astronomy and Astrophysics* and took me on as a co-author (*Annual Rev. Astron. Astrophys*. **24,** 127; 1986). This review is cited much more than our original paper. We were now charged with producing a balanced view, which meant a lot of further reading and discussion.

Forty years after, I would say that our work has been subsumed into the Bayesian school of statistical inference, since the entropy functions could be viewed as different priors in disguise. An alternative description that carries less baggage is "regularised maximum likelihood," This has played a role even as recently as the capture of images of the ring around the M87 black hole made by the Event Horizon Telescope in 2019. ■



Liquid crystals are an intermediate phase between a crystal and a liquid phase.

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Optical diffraction in chiral smectic-C liquid crystals

Evolution of our understanding of the fascinating physical properties of chiral smectic-C liquid crystals

K A Suresh

Sir Chandrasekhara Venkata Raman and his student Nagendra Nath published a series of papers in 1936 on the diffraction of light by a liquid in the field of a high frequency sound wave. This was theoretical work developed to explain the observed diffraction pattern obtained for light incident on a liquid medium of periodically varying refractive index arising from the passage of a high frequency sound wave. This is usually referred to as optical diffraction in the phase grating mode since the phase of an incident plane wavefront varies periodically when emerging from the medium without any variations in amplitude.

Thermodynamically, liquid crystals (LCs) are an intermediate phase between a crystal and a liquid phase. LCs are broadly classified into three types: nematic, smectic and cholesteric LC phases. The smectics are further classified into smectic A, smectic B, smectic C and so on. The smectic Cs that are made up of chiral molecules are classified separately as chiral smectic-C LCs (CSLCs). They are structures with a helical stack of layers in each of which molecules are tilted uniformly in a particular direction. The tilt direction spirals about the layer normal. Generally, the tilting of the molecules is coupled to the layer thickness resulting in a local biaxiality in the medium. When light is incident normal to the helical axis or twist axis, such a structure will act as a phase grating for light waves.

> *"Even today, the CSLCs are studied for their fascinating electro-optic and other physical properties."*

In the 1990s, Gobbalipur Shamanna Ranganath and Kattera Appanna Suresh, both then faculty members at the Raman Research Institute, applied Raman and Nath's theory to optical diffraction in CSLCs. PhD student P.B. Sunil Kumar collaborated with them in these studies. Their calculations implied extra orders which were odd orders in the diffraction pattern. They were always linearly polarised whereas the even orders were elliptically polarised. They also found wandering of intensity from lower orders to higher orders, with variation in the local birefringence of CSLCs (K.A Suresh. and P. B. S. Kumar *et al, Liq. Cryst.* **1**, 73; 1992). To verify these theoretical results, Suresh and his PhD student Yuvaraj Sah conducted experiments on a commercially available sample BDH-SCE-6 which exhibited a CSLC phase. They aligned the sample appropriately in the phase grating geometry by applying a high magnetic field. This configuration with the laser light (632.8 nm) incident normal to the twist axis of CSLC yielded an excellent diffraction pattern with sharp diffraction spots. Their experimental results turned out to be surprising (K. A. Suresh, Y. Sah, *et al. Phys. Rev. Lett.* **72,** 2863; 1994). The observed features were very different from the predictions of the original theory as extended to CSLCs in the paper by Suresh and colleagues published in 1992. The various orders in the observed pattern showed some unusual intensity and polarisation features. Depending upon the polarisation geometry, the intensities of some of the higher orders were much higher than that of the lower orders. For the incident linearly polarised light, the diffracted light was linearly polarised in a direction parallel to the twist axis in all the orders. These intensity and polarisation features contradicted the results of the original theory that had been extended to CSLCs.

It was soon realised that the theory was valid only for systems with low birefringence and for small enough sample thickness in which internal diffractions within the medium could be neglected. In reality, the material used in the experiments had a high birefringence and the sample thicknesses were on the higher side. Incorporating the internal diffraction required a more rigorous theory. Ranganath and Kumar adopted the theory of anisotropic dielectric gratings developed in 1983 (K. Rokushima and J. Yamakita *J. Opt. Soc. Am.* **73,** 7, 901–908; 1983). They applied this theory and formulated equations suitable to the optical diffraction in the CSLC system. Using the material parameters, they computed the intensities of different orders for varying sample thicknesses. The intensity values for proper choice of material parameters agreed well with the experimental results. The computations showed that the theory could also account for the polarisation features seen in the experiments, in the zero and higher orders of diffraction. It was satisfying to note that the experimental results and the theory matched so well.

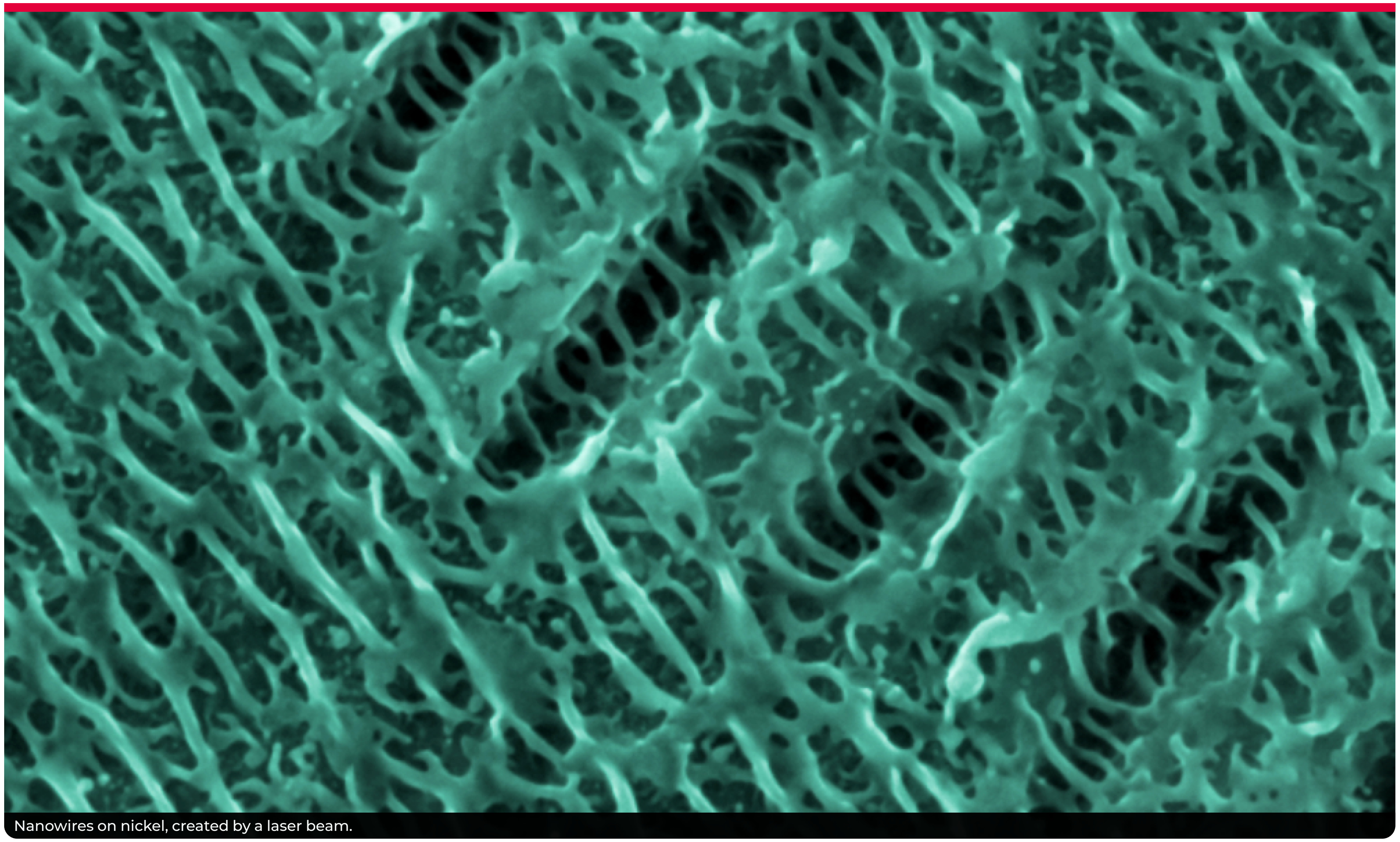
The experiments and theory have shown that CSLCs can act as an efficient phase grating for light waves. The birefringence of the medium can change by varying the sample temperature. Hence the intensity of the various orders of the optical diffraction can be tuned. This tuning of intensities has wide applications in optical communication.

CSLCs have drawn a lot of attention due to their distinctive helical structure. The existence of ferroelectricity in CSLCs has led to technological applications. The sub-microsecond dynamics and large electro-optic response has been exploited in the fast-switching display devices. Several studies have demonstrated a variety of physical properties exhibited by CSLC. For example, it exhibits pyroelectricity, electroclinical effect, shear-induced polarisation, second harmonic generation and many other interesting phenomena. Even today, the CSLCs are being studied for their fascinating electro-optic and other physical properties. ■

A quantum Langevin equations approach for transport in nanowires

A ground-breaking approach to investigating phonon transport

Abhishek Dhar



Nanowires on nickel, created by a laser beam.

GEORGY SHAFEEV/ SHUTTERSTOCK.COM

The formulation of a general theory of transport in many-body systems is one of the challenging problems in theoretical physics. Unlike the Gibbs-Boltzmann framework for systems in equilibrium, there is no general microscopic theory for systems that are out of equilibrium. A simple example is that of heat conduction where we take a wire and attach its two ends to heat reservoirs at different temperatures, say T_L and $T_R < T_L$. We expect the system to reach a steady state with a heat current, J, going from the hot reservoir to the cold one. One basic question is: how do we predict the value of the current, J, given the Hamiltonian of the system which specifies the system at a microscopic level?

One of the standard approaches is to use perturbation theory about the equilibrium state and this leads to the Green-Kubo formalism which provides us with formulas for transport coefficients, such as the thermal conductivity, in terms of equilibrium time-dependent correlation functions. However, these formulas are not useful to understand heat transport in nanowires in the low temperature regime where interactions between the heat carriers are effectively weak and we are in the regime of ballistic transport. For an electrically insulating wire, the mesoscopic regime is best described by treating the wire as a harmonic crystal. The heat carriers are the phonons and the main sources of scattering are impurities and defects present in the crystal and the contact between the wire and the reservoirs. A useful description of transport in this ballistic regime is the so-called Landauer-Büttiker approach[1] which views transport in terms of the transmission of phonons across the system from one reservoir to another. The heat current, J, is then simply the difference between the heat flux of left- and right- moving thermal phonons. An exact formal expression can be obtained for the heat current, J, and involves not only the Hamiltonian of the system but also the spectral properties of the reservoirs and details about the contacts, i.e, the system-reservoir couplings. For the case of electron transport, the standard microscopic derivation of the Landauer-Büttiker results uses the Keldysh formalism and in the context of transport, this is referred to as the nonequilibrium Green's function (NEGF) approach[1].

The 2006 paper on heat transport in harmonic lattices which originated from research carried out at the the Raman Research Institute[2] presented a new derivation of NEGF-type results for phonon transport using a quantum Langevin equations (QLE) approach. The QLE approach is based on an idea by Paul Langevin[3] of describing the interaction of a Brownian particle with the fluid in which it is moving. Langevin proposed that the effect of the thermal environment can be simply captured by adding two extra terms to the equations of motion of the Brownian particle – a dissipative term and a noise term. The noise and dissipation are related to each other via a fluctuation-dissipation relation and which involves the bath temperature. For quantum systems, finding the correct Langevin equation is more subtle and one must start with a microscopic model of the reservoirs. The QLE for a quantum particle was first proposed in a seminal paper by Ford *et al.*[4] which described the motion of a single particle in a thermal environment modelled by an infinite collection of oscillators. In this work, Abhishek Dhar and Dibyendu Roy replaced the Brownian particle by the wire that is interacting simultaneously with two thermal reservoirs at different temperatures and evolves to a nonequilibrium steady state.[2] The QLE approach had earlier been used in a few papers to understand phonon transport in nanowires[5–7]. In their 2006 work, Dhar and Roy considered harmonic networks in the most general setting, derived the QLE of the system and solved these to compute various nonequilibrium steady-state properties such as the heat current and all two-point correlations. The most significant achievement was that the authors were able to cast all the results in the same form as the NEGF expressions for electronic systems.

Apart from providing a much simpler but still rigorous microscopic derivation of transport properties, as compared to the Keldysh (approach applied later to phonons[8]), the QLE method provided a new and physically appealing perspective where transport is viewed as an open-system problem where the reservoirs are sources of quantum noise and dissipation. Dhar and Roy's work provided a unification of many earlier studies on transport in electronic and phononic systems in both classical and quantum systems. The QLE approach has now become a powerful tool for understanding transport and fluctuations in mesoscopic systems, a topic that is currently of much theoretical and experimental interest. ■

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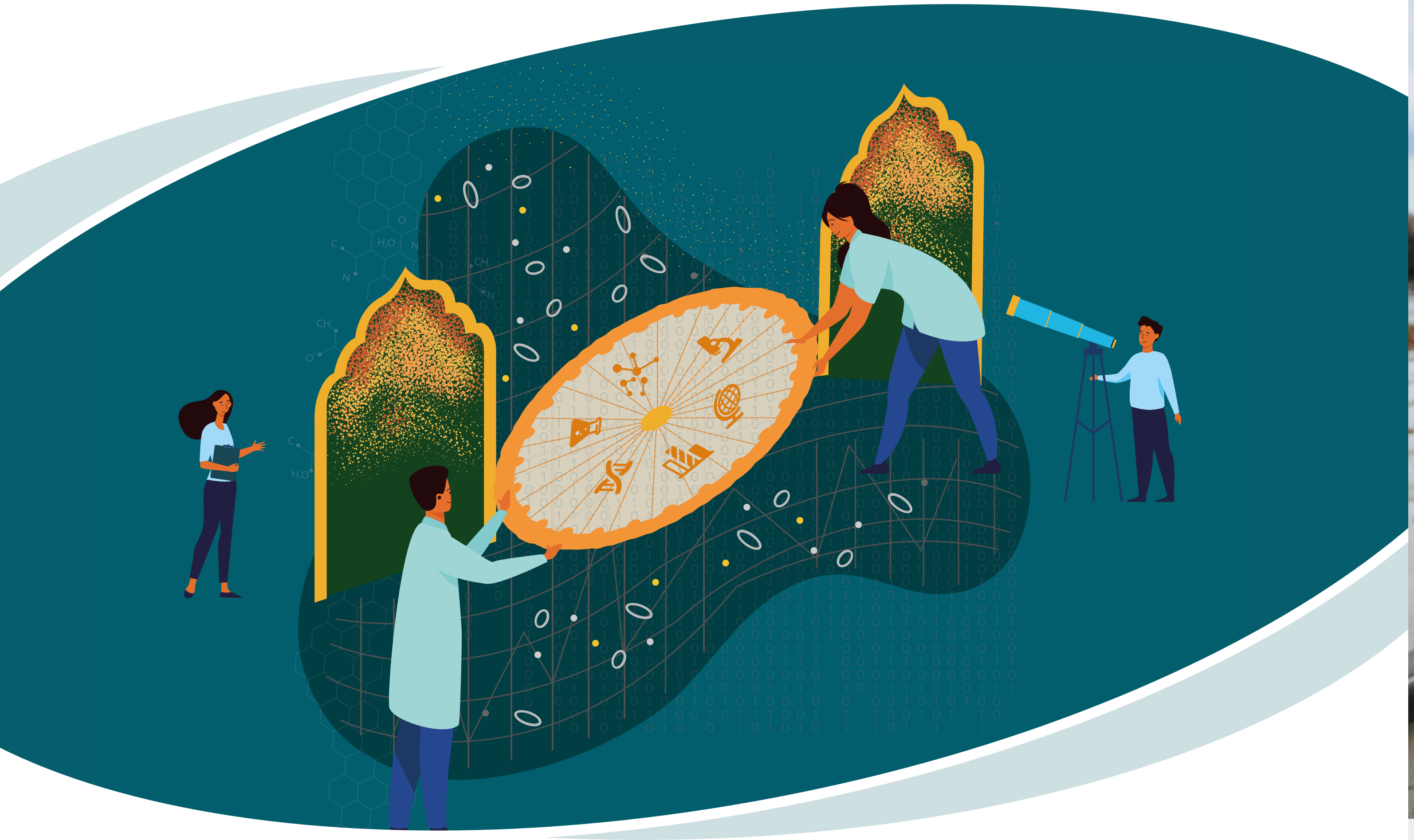

Signals from the depths of the cosmos

Probing cosmic dawn and the continuing quest for the elusive 21 cm signal

Saurabh Singh and Mayuri S. Rao

One cannot help but wonder about the origin of the twinkling dots that span the night sky. The idea of the birth of the very first stars is intriguing given that the environment they would have formed in would have been very different from today. After their formation, radiation from the stars ionised the hydrogen gas in the Universe. The period, beginning with the birth of the first stars and galaxies followed by the reionisation of the Universe is often referred to as the cosmic dawn and epoch of reionisation[1].

This period lasted roughly from 100 million to 900 million years after the Big Bang. However, it is exceptionally challenging to observe these distant epochs directly. In the absence of observations, we know truly little about this period from the nature of these first sources of radiation to the exact timeline of the processes that occurred within it.

At the Raman Research Institute, the quest to understand the cosmic dawn was initiated by Ravi Subrahmanyan and N. Udaya Shankar. They envisioned telescopes that could conduct sensitive observations to understand the nature of the first stars and galaxies. One of the best ways to do so was to exploit the fact that hydrogen gas is abundant in the Universe. It was well established and observed[2], that hydrogen gas had a unique radiation emitted at a frequency of 1,420.405 MHz or equivalently at a wavelength of 21 cm. The sources of radiation during the cosmic dawn would imprint their signature in the brightness of this 21 cm signal, changing its shape and strength over cosmological timescales

With this goal in mind, the Shaped Antenna measurement of the background Radio Spectrum (SARAS) experiment was initiated at RRI. It aims to detect the mean brightness of 21 cm radiation using a single antenna with calibratable receivers. SARAS, along with its contemporaries, marked the emergence of small-scale precision experiments towards studying the cosmic dawn. The beauty of such experiments lies in their iterative abilities – they can be designed, developed, deployed and upgraded in a continuous cycle. The experiment requires ingenuity in antenna and electronics design, exceptional care in construction, meticulous selection of an observing site and algorithmic development for data modelling. Such a diverse range of activities require an integrated approach in science and engineering. As a result, the SARAS team comprises scientists, engineers and students who specialise in different domains.

The first stars were formed in a vastly different environment from that of today.

ALAMY STOCK PHOTO

> *"The beauty of such experiments is that they can be designed, developed, deployed and upgraded in a continuous cycle."*

The reason for such a high-precision design becomes clear when one looks at the challenges involved. The signal from the cosmic dawn is expected to arrive on Earth stretched in wavelength to meters and lowered in frequency by the expansion of the Universe to lie in the radio frequency band 50–200 MHz. The celestial signal is exceptionally faint as it is buried in sky radio waves that come to us from the gas in our own Galaxy, the Milky Way, which are a million times brighter. More unfortunate for astronomers is that this cosmic signal is in a radio wavelength band used by terrestrial communications equipment and TV and FM radio stations, which makes detecting the extraterrestrial signal extremely difficult.

In 2018, soon after SARAS 2 became the first experiment to constrain the properties of the first generation of stars via 21 cm observations[3], the Experiment to Detect the Global EoR Signature (EDGES) led by astronomers at Arizona State University and Massachusetts Institute of Technology claimed to have detected the global 21 cm signal[4]. The strength of the reported signal from the cosmic dawn was wildly different to theoretical predictions prompting several speculations about how the Universe might be different compared to the accepted current understanding. These speculations included exotic physics, non-standard cosmology, new populations of early galaxies during the early Universe and new models of dark matter that may have resulted in such an unusual signal[5]. However, appreciating that errors in instrument calibration might result in spurious detections in such difficult measurements, cross-verification of the claim became a priority.

SARAS took a different turn in its observations to reach the sensitivity required for such a cross-examination. To ensure a clean measurement with SARAS, its antenna was floated on a raft on water. In an expedition in early 2020, the radio telescope was deployed in lakes in northern Karnataka, on Dandiganahalli Lake and the backwaters of Sharavati, all in India. After a rigorous statistical analysis, SARAS[3] did not find any evidence of the signal detected by the EDGES experiment[6]. The presence of the signal was rejected after a careful assessment of the measurement's uncertainties. The findings implied that the detection reported by EDGES was likely a calibration error. SARAS[3] was indeed the first experiment to reach the required sensitivity to cross-verify the claim of signal detection. This research restored confidence in our understanding of the evolving Universe, re-establishing the prevailing standard cosmological model.

However, astronomers still need to know what the actual signal looks like. Having rejected the EDGES claim, the SARAS experiment is geared towards discovering the true nature of cosmic dawn. Since the publication of these findings, SARAS has undergone a series of upgrades and has conducted observations at a few radio-quiet locations in India. In the meantime, another RRI experiment is preparing to complement this quest for the signal hunt from space with PRATUSH – Probing ReionisATion of the Universe using Signal from Hydrogen. Given the challenges from ground-based observations, PRATUSH will fly in lunar orbit and conduct cosmological observations from the far side of the moon, which is expected to be pristine with no terrestrial radio frequency interference. It is currently in the pre-project studies phase, supported by the Indian Space Research Organisation.

The faint nature of the signal requires meticulous calibration of the telescope and robust cross-verification from different experiments. Therefore, SARAS and PRATUSH conducting observations from vastly different environments with unique challenges form an ideal set-up to look for the elusive 21 cm signal. A robust detection of the signal would help us unravel this last remaining gap in the history of our Universe. ■

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Cortical actin and the spatiotemporal organisation of cell surface molecules

The development of a theoretical model for the cell membrane that includes nonequilibrium forces of actomyosin

Kripa Gowrishankar and Madan Rao

The cell membrane is the site of many vital processes and an important subject of research in cell biology. It also poses many interesting questions to physicists broadly concerning shape, organisation and interactions between its constituents.

The highly influential *Fluid Mosaic model* of the cell membrane, by S. J. Singer and G.L. Nicolson (Science, 1972) proposed that the cell membrane is a lipid bilayer, made up of mainly phospholipids and cholesterol, forming a 2D homogeneous fluid in which integral proteins and carbohydrates are embedded. Within the membrane, molecules were assumed to diffuse around thermally, under the influence of short-range intermolecular forces. This broad picture continues to be the basis of understanding several aspects of membrane behaviour. Subsequently , K. Simmons and E. Ikonen (Nature, 1997), proposed a variant of the above known as the *Raft model*, where the cell membrane forms lateral functional domains enriched in long-chain saturated fatty acids and cholesterol. These models are fundamentally based on equilibrium thermodynamics.

n our study and in earlier ones by our group, we demonstrated that these equilibrium models were insufficient to understand the spatiotemporal organisation of a large class of lipid-tethered proteins on the cell membrane, e.g. glycosylphosphatidylinositol-anchored proteins (GPI-APs), an upper leaflet membrane protein, known to associate with sphingolipids and cholesterol. The model we proposed was a radical departure from the earlier equilibrium ones, and viewed the cell membrane as being driven by active, out-of-equilibrium forces arising from its interaction with the adjoining cortical actin and myosin (Gowrishankar, K. *Cell* **149**, 1353–1367, 2012), in addition to the usual thermodynamic forces.

This *Active Composite model* was a result of two independent streams of investigation. One was our long standing collaboration with Satyajit Mayor's group at the National Centre for Biological Sciences (NCBS), who were using novel fluorescence-based assays to understand the local organisation of endocytosis of GPI-APs. The second was our theoretical investigations in the development of Active Soft Matter and Active Membranes.

Our first contribution, following a rather detailed analysis of the fluorescence data of GPI-APs, was to show that the GPI-APs, while associating with sphingolipids and cholesterol, were organised in a mixture of monomers and tight nanoclusters, containing around 4-5 molecules. This was fundamentally different from the perception of `Rafts' that was popular amongst scientists at that time. In addition, we found that the fraction of GPI-APs in nanoclusters was independent of the total number, thus apparently violating equilibrium mass-action. These findings appeared in Cell, 2004, and marked the beginning of a fruitful collaboration between the experimental cell biology group at NCBS and the theoretical soft matter group at RRI.

Next, by deploying novel fluorescence anisotropy techniques and analyses methods, we studied the kinetics of aggregation and fragmentation of these nanoclusters and their spatial distribution. The nanoclusters appeared to show strong correlations with regions of contractile actin. Analysis of the kinetics suggested that the nanoclusters showed high and constant rates of aggregation and fragmentation at temperatures above 20°C, which reduced dramatically below this temperature. Further, the rates were sensitive to actin perturbations, strongly suggesting that the upper leaflet protein was sensing the dynamics of the underlying actin cortex. This study appeared in Cell, 2008.

By 2006, our independent work on active systems was already preparing us to think in terms of an active cell membrane driven by actomyosin stresses. We therefore started building up the elements of such a theoretical model, together with coming up with predictions that could be experimentally tested (or falsified!).

In our model (Cell, 2012), we viewed the cell surface as an Active Composite of a multi-component, asymmetric cell membrane juxtaposed with a thin actomyosin cortex. The actomyosin cortex just adjacent to the cell membrane comprises of short actin filaments ("formin"-nucleated) and Myosin minifilaments, that bind to and drive the actin filaments with the help of adenosine triphosphate (ATP), resulting in active currents and stresses at the cell membrane. These could be studied using a coarse grained hydrodynamic framework in terms of the concentration and orientation of actomyosin. The resulting patterns at steady state showed a variety of defect structures, including actin asters. By coupling the dynamics of actomyosin to membrane components such as GPI-APs, we showed that the formation of actin asters in the cortex could drive their nano-clustering. This clustering is a uniquely active phenomenon and occurs in the absence of any attractive interactions between the clustered components. Introducing an active noise in the hydrodynamic equations lead to a constant fragmentation and aggregation of asters and hence of nanoclusters. The theory made several predictions on the kinetics of fragmentation-aggregation of nanoclusters, and the statistics of density fluctuations, including their extreme statistics, all of which were verified in experiments presented in the same paper. This picture of active clustering of membrane molecules has subsequently been verified in *in-vitro* reconstitution experiments carried out in our group (PNAS, 2016). Our study, while putting forth two new ideas, namely the involvement of actin and myosin in the organisation of cell surface molecules, and the importance of nonequilibrium (active) forces in driving and maintaining that organisation at nanoscales, also opened the door to many outstanding questions, which we and others have pursued over the years.

The current picture of the Cell surface that emerges from these studies is the following : the cell surface is a nonequilibrium, active system built from a composite of an asymmetric multicomponent membrane and multicomponent actomyosin cortex. The cortex applies active stresses and currents on the inner leaflet of the cell membrane. Specific molecules on the inner leaflet of the cell membrane, such as Phosphatidyl Serine (PS), respond to these active stresses and transmit them to long-chain saturated lipids, such as GPI-APs, on the outer leaflet via transmembrane interactions that involves cholesterol and sphingolipids. These active stresses drive molecular clustering (proteins and lipids) at both *nano and meso* scales, giving rise to an *Active Emulsion*. This continues to be an active field of research. ■

The phospholipid bilayer that forms the membrane around all living cells.

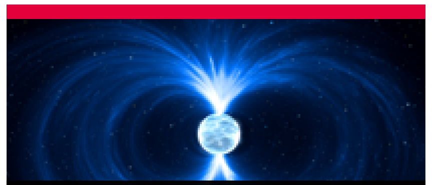
KATERYNA KON/ SPL/ GETTY IMAGES

Quantum tangling in extremely dense stars

RRI's landmark probe into decay of neutron star magnetic fields

Dipankar Bhattacharya and Sushan Konar

In June 2023, the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) published an analysis of its 15-year data set containing the first evidence of slowly undulating gravitational waves passing through our galaxy. This difficult detection was made possible by using a network of exotic stellar objects called millisecond pulsars to turn a good part of our galaxy into a huge gravitational-wave antenna.



The rotational and magnetic evolution of neutron stars are coupled.

VICTOR DE SCHWANBERG SPL / GETTY IMAGES

What are these pulsars? In 1967, Dame Jocelyn Bell Burnell, a PhD student at Cambridge University supervised by Antony Hewish, discovered something that gave off periodic pulses at radio wavelengths. When stars many times more massive than our sun exhaust their nuclear fuel, they eventually collapse and produce supernovae. Sometimes the explosion leaves behind a neutron star, the collapsed stellar core with a mass like that of the sun but with a radius of about 10 kilometres. At the extreme densities of their interior, which is nearly a billion tons per cubic centimetre, most protons combine with electrons to become neutrons. These highly compact stars are home to some fascinating physics. They can spin incredibly rapidly and possess ultra-strong magnetic fields (up to 100 thousand million Tesla). Many of them produce beamed electromagnetic radiation. As the star rotates like a lighthouse, we observe pulses of light, hence the name pulsar. The radiation carries away the rotational energy of the star and over time the pulsar spins down.

Astronomers realised that pulsars belong to two distinct classes – those born with a spin and those spun up by accreting material from a binary companion. The latter group would act as pulsars before the accretion starts and again after the accretion stops, spinning much faster the second time. These objects were investigated extensively at the Raman Research Institute and were christened recycled pulsars[3]. Millisecond pulsars, with spin periods shorter than 20 milliseconds, belong to this class.

Importantly, this investigation showed that the spin period of a neutron star in the recycling process depends on its magnetic field strength and the rate at which it accretes mass[4]. These two factors determine the distance from the neutron star at which the swirling flow of the infalling matter is arrested and converted to directed inward motion. The shorter this distance, the faster the swirl, deciding the maximum spin-up of the neutron star. To be spun up to millisecond periods, a neutron star requires a near-maximum accretion rate coupled with an extremely weak magnetic field — nearly four orders of magnitude smaller than the average magnetic field strength of pulsars[5].

Why are the magnetic fields of millisecond pulsars so weak? Initially this was attributed to neutron stars being much older than the rest, perhaps they lost their magnetic field over time due to spontaneous ohmic decay, like currents flowing through a resistive wire. This, however, was incompatible with observations[6] and researchers realised that the decrease in field strength was somehow related to the binary evolution itself[7]. The popular idea was that hot plasma material settling on the surface of the neutron star would progressively screen its magnetic field[8]. But such screening was shown to be transient and the field would re-emerge after accretion stops[9]. With this background, the 1990 paper by RRI's Ganesan Srinivasan and Dipankar Bhattacharya and Ioffe Institute's Alexander Muslimov and Anatoly Ivanovich Tsygan[10] proposed a radical idea born during the 1989 meeting on condensed matter properties of neutron stars at the International Centre for Theoretical Physics in Trieste.

The idea built on the interaction of superfluid vortices and superconducting fluxoids proposed by James Sauls a year earlier[11]. In the interior of a neutron star, the neutrons and the protons are expected to form spatially co-located quantum condensates — respectively a superfluid and a superconductor. The rotation of the star is carried by Onsager-Feynman vortices in the superfluid, and the interior magnetic field is carried by Abrikosov fluxoids in the superconductor. The two interact via strong nuclear forces. The rotational and magnetic evolution of the star are thus coupled. Initial spin-down of the star expels the vortices and the associated fluxoids, leading to reduced field strength. Once accretion-driven spin-up starts, the remaining fluxoids are pushed deeper into the stellar core, freezing this residual field strength. This picture explained all the observed features of the neutron star population – the magnetic field decay of young pulsars, the preponderance of binaries among low-field pulsars, and the long-term stability of the reduced but substantial field strengths of old neutron stars.

This work spawned a variety of investigations resulting in many expected consequences, including stress fracture and creep of the crust of the star[12], related dissipation, heating, chemical imbalance[13] and other detailed microphysical processes. Some of these are still being actively pursued three decades later.[14] This research remains one in a series of landmark contributions on neutron stars by the RRI astrophysics group, which also pioneered the idea of the recycling process[3–5] and predicted the gamma ray emission from millisecond pulsars[15] long before its discovery. ■

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