CHAPTER 18

Indian Achievements in Astronomy, Astrophysics, Relativity and Cosmology

Jayant V. Narlikar

jvn@iucaa.ernet.in

The chapter begins with describing the pioneering work of Meghnad Saha on stellar atmospheres, followed by the work in general relativity and cosmology in two distinct schools: N. R. Sen in Calcutta and V. V. Narlikar in Banaras. P. C. Vaidya's work (Banaras) on radiating stars is very much used today, as is B. Datt's (Calcutta) work on gravitational collapse. The Raychaudhuri equation in relativistic cosmology set the trend for future work on space-time singularities in general relativity. India has been one of the major places where alternatives (J. V. Narlikar) to the big bang cosmology have flourished. The Madras Observatory made its mark in optical observations, but post-independence India saw new facilities being created at Nainital, Kodaikanal, Kavalur, Udaipur, Gurushikhar, Han Le and Giravali. Space astronomies took off with balloons, rockets and satellites. The chapter ends with a brief critique of what have been the strengths of Indian contributions to astronomy and astrophysics, and their possible weaknesses.

INTRODUCTION

It is well known that the period of about seven centuries, from Aryabhata to Bhaskaracharya II (c. 476–1150), was the golden age of Indian astronomy. During this period, Europe was little developed astronomically and the Arabs found it attractive to come and translate Indian works into Arabic. The momentum after this period seems to have fizzled out, although there were a few isolated cases of brilliance from time to time. In the meantime, science began to get a boost in Europe and with the arrival on the scene of Copernicus, Kepler, Galileo and Newton, astronomy made a strong beginning in the sixteenth and seventeenth centuries. These times also coincided with the beginning of colonization of the East by the West. India had mainly the French and the British to contend with. While one deplores the principle and practice of colonization, one cannot deny that the scientists from these countries helped revive science in general and astronomy in particular in India. The details of these inputs are discussed by Kochhar and Narlikar.[1]

The British and French astronomers initially came to India to make observations of celestial events such as planetary transits and solar eclipse. However, when the British had secured a firm foothold in India, they set up the Madras observatory. Its purpose was to determine the reference meridian and carry out mapping of the coast. Later, it was shifted to Kodaikanal and made significant studies of the Sun, especially under Evershed in the early part of the twentieth century. Even today, solar observations are carried out everyday from the observatory. For details of this and other observational developments in the late colonial India, the reader is referred to the account of Kochhar and Narlikar.[1]

EARLY INDIAN CONTRIBUTIONS TO THEORETICAL ASTROPHYSICS

Although the Indian response to observational astronomy was rather lack-lustre, it was path breaking in the field of theoretical astrophysics. While the well-placed Calcuttan astronomy enthusiasts were forming an astronomical society, unknown to them, a bright lad in the backwaters of East Bengal was making his acquaintance with astronomy. Meghnad Saha (1893–1955) wrote an essay on comet Halley in Bengali for the Dacca College magazine. As lecturers in physics in the Calcutta University, Saha and Satyendranath Bose (1894–1974) brought out in 1920 an English translation of Einstein's articles on relativity. Reviewing it, the science magazine *Nature* wrote on 26 August 1922, 'Provided it is studied with care, the translation will nevertheless be of service to those who are unfamiliar with German, and wish to grapple with the pioneer works on these subjects, some of which are rather inaccessible'.

Stimulated by Agnes Clerke's popular books on astrophysics, Saha published in 1920 his epoch-making work on the theory of high-temperature ionization and its application to stellar atmospheres. Saha's demonstration that the spectra of far-off celestial objects can be simply understood in terms of laws of nature as we know them on the earth, transformed the whole universe into a terrestrial laboratory and laid the foundation of modern astrophysics. In 1923, Saha moved to Allahabad University as professor of physics where he set up a school of astrophysics, training outstanding students like Daulat Singh Kothari (1906–93). Saha was the first to point out (in 1937) the need to make astronomical observations from outside the earth's atmosphere. He returned to Calcutta in 1938 as Palit Professor. Saha and Bose, like Raman, were the foundation fellows of the Indian National Science Academy. Saha became its President during 1937–38, Bose in 1949–50, whereas Kothari held that position during 1973–74.

At Madras, Subrahmanyan Chandrasekhar (b. 1910) for the first time applied the theory of special relativity to the problems of stellar structure and obtained preliminary results on white dwarf stars. His rigorous deduction of the result at the University of Cambridge a few years later that a white dwarf cannot have a mass more than 1.4 times the mass of the Sun came to be known as the Chadrasekhar mass limit. Chandrasekhar belatedly received the physics Nobel Prize in 1983 for this and other works on gravitational physics.

It is not very well known that during 1943–45 the Government of India made sincere efforts to bring Subrahmanyan Chandrasekhar from Chicago to Kodaikanal. He was offered a salary three times the usual. Chandrasekhar, however, was unwilling to be placed in charge of the routine work of any observatory and would prefer to have a job in university. Attempts of a similar kind were also made by Dr Sarvepalli Radhakrishnan at the Banaras Hindu University (BHU) and Dr Homi Bhabha at the

Tata Institute of Fundamental Research (TIFR). Although Meghnad Saha felt that 'Dr Chandrasekhar ought to return to India to train our own boys', this was not to be.

PIONEERING INDIAN RELATIVISTS

Curiously, unlike the Indian astrophysicists, pioneering relativists were trained abroad. Nikhil Ranjan Sen (1894–1963), a class-fellow of Saha and Bose, joined as a lecturer in applied mathematics at Calcutta in 1917. He obtained his D.Sc. in 1921, but went to Berlin where he obtained his Ph.D. under the supervision of Max von Laue. Sen's was the first Indian doctorate in relativity and he joined the Indian National Science Academy (INSA) as a foundation fellow. Vishnu Vasudeva Narlikar (1908–91) obtained his B.Sc. in 1928 from the Royal Institute of Science, Bombay, and left for the University of Cambridge for higher studies, thanks to the financial assistance from Bombay University, Kolhapur state, and the J. N. Tata endowment. He passed the Mathematics Tripos with distinction in 1930 and went on to win the Rayleigh Prize for his astronomical researches under Arthur Eddington. Spurning an offer to go to the California Institute of Technology, USA, he accepted an invitation from Madan Mohan Malaviya, the Vice Chancellor of BHU, and came to Banaras as the head of the mathematics department in 1932, where he remained for the next 28 years. He trained and guided a large number of students, including Prahlad Chunilal Vaidya (b. 1918), author of the well-known Vaidya metric (1943) for the gravitational field of a radiating star. In 1955 came Amal Kumar Raychaudhuri's (b. 1923) equation that has played a crucial role in the investigations on singularity in relativistic cosmology. We will return to the works of Vaidya and Raychaudhuri later.

In 1938, B. Datt from Sen's group gave the solution for a gravitationally collapsing spherical ball of dust. This solution was published in *Zeitschrift für Physik* in Germany.[2] It anticipates the more commonly known solution of Oppenheimer and Snyder that appeared in a Western journal a few years later.

ON THE EVE OF INDEPENDENCE

By the time the Second World War came to an end, it was clear that British rule in India would soon be over. Plans were, therefore, afoot to set the scientific agenda for the future. Twenty years previously, the British director-general of observatories had offered to Saha the number two position under Evershed at Kodaikanal. Now, in December 1945, Saha led a five-member committee including the Indian director-general of observatories to Kodaikanal to prepare a plan for 'astronomical and astrophysical observatories in India'. The Saha Committee proposed updating of astronomical facilities including, as part of a long-range plan, the establishment in northern India of an astronomical observatory provided with a large-sized telescope for special stellar work. The Saha report came in handy 20 years later when Vainu

Bappu successfully pleaded for a stellar spectroscopic observatory at Kavalur in Jawadi Hills, Tamil Nadu. (The observatory has since been named after Bappu.) As a follow-up of Saha's report, and on his own initiative, in 1955 a National Almanac Unit (renamed Positional Astronomy Centre in 1979) was set up in Calcutta with a view to helping the traditional almanac makers update their astronomical elements.

The year 1945 also saw the establishment of TIFR in Bombay. Its founder was Homi Jahangir Bhabha (1909–66), a brilliant physicist who shared Jawaharlal Nehru's vision of a scientific India as well as his aristocratic background. Additionally, he was related to the wealthy and enlightened industrial family of the Tatas. (Sir Dorab Tata was married to Bhabha's paternal aunt Meharbai in 1898.) An important item on TIFR agenda was 'experimental research on cosmic rays', in which Bhabha was personally interested. The experiment involved sending payloads attached to balloons into the atmosphere, which in the course of time led to the advent of space astronomies in India. Indeed, India's entire space programme was to come out of such initial efforts. Its initiator Vikram Sarabhai was in turn inspired by Bhabha's pioneering work in India's atomic energy programme. It was also with Bhabha's support that radio astronomy was successfully introduced in the 1960s by Govind Swarup (b. 1929).

At the time of Independence in 1947, India could boast of only two, rather outdated, observatories—the central government's Solar Physics Observatory at Kodaikanal that stood where Evershed had brought it in 1911, and Osmania University's non-teaching Nizamiah Observatory with equipment of still earlier vintage. Saha Committee's rather pious recommendation for upgradation of the astronomical facilities was on record, but there was nobody at hand to drive home the advantage. Bhabha's nascent institute was still housed in his aunt's mansion, but was poised for take off in a big way. And finally, there were a number of universities that would multiply but fail to keep the early promise.

Today, the Indian astronomical establishment has several observatories and research institutions. To name the important ones: The Indian Institute of Astrophysics (IIA), the Raman Research Institute (RRI), both in Bangalore, TIFR in Mumbai, which runs the National Centre for Radio Astrophysics (NCRA) in Pune, the Physical Research Laboratory (PRL) in Ahmedabad, the Inter-University Centre for Astronomy and Astrophysics (IUCAA), the Aryabhatta Research Institute (ARIES) in Nainital and the Udaipur Solar Observatory (USO) in Udaipur. The Indian Space Research Organization (ISRO) also runs a space laboratory in Bangalore called the ISRO Satellite Applications Centre (ISAC). Several (around 30) universities offer astronomy/astrophysics as an option in their master's programme and IUCAA helps coordinate university efforts in astronomy and astrophysics.

It is against this background that we now describe the highlights of research in astronomy and related areas in the half century or so of the newly independent India. For convenience, we have divided the field into different topics.

THE SUN

The Kodaikanal Observatory of IIA and USO are exclusively devoted to the studies of the Sun. Solar studies form a major part of activity at Nainital and figure in the work of other observatories.

The chief highlight of the Kodaikanal Observatory's work has been the 1909 discovery of the Evershed effect, namely, the outward radial flow of gases in sunspots. Later work revealed that there is a reverse flow at chromospheric heights. Over the years, the observatory has obtained a long stretch of white-light solar pictures and spectroheliograms. The Ca II K pictures tell us about the upper chromosphere, $H\alpha$ pictures about the lower chromosphere, while white-light pictures provide information about sunspots. The Kodaikanal database has been used to discover a number of significant correlations among solar phenomena. At the same time, high resolution spectra obtained with the tunnel telescope have been analysed to yield important results.

It has been shown from Kodaikanal that time variation of total plage area on the visible hemisphere of the Sun carries the definite signature of solar rotation. This correlation provides a convenient method for estimating the rotation of stars that have chromospheres. The solar chromospheric rotation rate has been found to show variations on the time scales of 2, 7, and 11 years. Studies have been initiated to obtain information on solar rotation from precise measurements of the old sunspot data. The $H\alpha$ data for 1905–82 have been used by the IIA scientists to investigate the global properties of large-scale magnetic fields. It has been shown that the fields migrate towards the poles with a variable velocity of up to 30 m sec^{-1} depending on the phase of the solar cycle. It has been found that there is a correlation between Ca II K emission and the magnetic field strength in the plages. This correlation can be used for estimating the magnetic fields of stars from their Ca II K spectra. It has been shown that a day or two prior to the occurrence of a flare, there occurs a change in the orientation of the $H\alpha$ filament.

Using fine-quality solar Ca II K spectra, IIA scientists have concluded that the Wilson–Bappu relationship between K emission line widths and the absolute magnitude of stars mostly arises due to the elements that make up the quiet atmosphere. This work suggests that the stars that deviate the most from the Wilson–Bappu relationship are the best candidates for studying stellar activity cycles. Ca II K line profiles of the Sun obtained in integrated light have been found to vary with the phase of the solar cycle. This indicates that the Sun is a variable star. It has been found that the size of the Ca II K (supergranular) network is a function of the solar cycle: The cells are smaller at the solar maximum than at the minimum. It has also been shown that within the bright supergranular boundaries there exist dark regions of 4000–6000 km size. These regions are characterized by relatively large downflow velocities of 5–8 km sec^{-1} compared to neighbouring horizontal velocities of about 0.5 km sec^{-1}.

Detailed studies have been carried out at Kodaikanal of velocity and intensity fluctuations in selected solar spectral lines, with special reference to 5-minute oscillations. It has been found that intensity fluctuations are coherent over scale lengths of about 10,000 km on solar surface. The newly-built spectropolarimeter has recently been used to obtain a large number of spectra in quick succession. This facility promises to provide new results in areas such as sunspot seismology, speckle reconstruction of solar features, and time evolution of solar flares.

USO is a participant in the international programme of the Global Oscillation Network Group (GONG). Udaipur has been selected as one of the six sites distributed around the globe for making solar velocity oscillation observation for helioseismology. The observatory has taken part in a number of international programmes, for example, solar maximum year, solar maximum mission satellite and Flare 22/Max '91.

From a large collection of chromospheric observations made from Udaipur, a photographic atlas of some typical examples of chromospheric activity has been published. The dynamics and evolution of several solar flares and mass ejections have been studied. From a study of proper motion of sunspots, it has been possible to estimate the build-up and release of energy in flares. Modelling of magnetic-field structure in post-flare loops and flaring arches and the study of the stability of dark Hα filaments on the disc are being carried out.

Patrolling of the Sun is done regularly at the Uttar Pradesh State Observatory (now renamed ARIES), Nainital to record and analyse flares, surges, prominences and other active features. The relationship of the morphology of the active features with mass motions and prevalent magnetic fields is sought. Correlations among the optical, microwave, X-ray emissions and sudden ionospheric disturbances have been investigated. The existence of active longitudes on the Sun has been postulated. Relationships between coronal holes, coronal mass ejections and solar flares have also been studied.

The Sun has been observed at decametre radio waves using the Gauribidanur telescope. Maps have been produced of continuum emission from the quiet Sun and the active regions. The compound grating interferometer has been used to make high resolution (3 arcmin) one-dimensional scans of the Sun. These scans have in turn been used to measure the variations in the east–west diameter of the undistributed Sun, active regions and coronal holes.

Expeditions to observe total solar eclipses have been an important part of work at IIA. The 1970 total solar eclipse revealed the rather unexpected presence of Hα emission in the solar corona. Multislit spectroscopy of the solar corona carried out during the successive 1980 and 1983 total solar eclipses has thrown significant light on the physical processes in the corona. First, it has been shown that ions have larger random motions in closed coronal loops than in the open. Second, at the time of increased solar activity, turbulence shows a significant increase. Third, the mechanism for excitation of ions in the corona is not uniform, with collisional excitation dominating near the solar limb and radiative excitation in farther regions. In addition, photometric and polarization measurements of the coronal structure have often been carried out.

IIA results support the view that there are no large-scale mass motions in the solar corona. On the other hand, coronal interferograms obtained during the 1980 and 1983 eclipses by scientists from PRL Ahmedabad, have been interpreted as evidence for the existence of large mass motions, especially during the active solar phase. The passage of the path of totality of the total solar eclipse of 16 February 1980 over the Japal–Rangapur Observatory (JRO) offered a unique opportunity to study the corona, using a large telescope. JRO astronomers carried out a two-colour polarimetric study of the corona. Besides giving electron density and temperature in the corona, the study confirmed the dependence of the brightness of the F corona on wavelength. Variation of the 3 cm radiation from the Sun during eclipse was also studied.

A three-member team from IIA observed the total solar eclipse of 3 November 1994 from Putre in north Chile. More important from the Indian point of view was the total solar eclipse of 24 October 1995, which was seen from a stretch of land extending from Iran in the west to Cambodia in the east. The path of totality passed through the states of Rajasthan, Uttar Pradesh, Bihar and West Bengal. A number of international scientific teams including those from IIA visited north India for the eclipse.

The continent of Antarctica provides a round-the-clock view of the Sun. In the local summer of December 1989 to March 1990, a three-member team from IIA and UPSO set up a small observatory at the Maitri station. A combination of a polar heliostat and a 10-cm aperture, f/30 objective lens was used to obtain pictures of the Sun in the light of the Ca II K line. Uninterrupted data extending over as long as 106 hours have shown that the average lifetime of a supergranular cell is about 22 hours. It has been shown for the first time that there is a correlation between lifetime and size of a cell in the sense that larger cells live longer. Also, cells associated with remnant magnetic fields live longer than those of comparable size in field-free regions.

Scientists at TIFR have taken part in worldwide efforts to understand the deep interior of the Sun. These efforts include trying to explain the observed low flux of solar neutrinos and modelling the 5-minute oscillations of the solar surface. Theoretical aspects of various solar phenomena are being studied at IIA, TIFR, National Physical Laboratory (NPL), New Delhi and elsewhere. Theoretical investigations into the existence of a number of molecular species (diatomic, triatomic and ionic) have been carried out at ARIES. Molecular constants such as oscillator, strengths, dissociation energies, Frank–Condon factors and partition functions for some molecules have been calculated. Turbulent velocity for the solar photosphere has been determined using centre-to-limb CH-line profile variations.

Extensive studies at the National Centre for Radio Astrophysics (NCRA), Pune have shown that the spectrum of turbulence in the solar wind is best described by a power law with an 'inner scale' rather than by a Gaussian. This makes it possible to estimate the solar wind velocity from single-station observations alone. Velocities thus estimated are in close agreement with those derived from the conventional three-station measurements. This powerful technique was used to study transients in the solar wind and the dependence of solar wind velocity on heliographic latitude and on the solar cycle.

SOLAR SYSTEM STUDIES

A sky survey using the 45-cm Schmidt telescope was begun at the Vainu Bappu Observatory (VBO), Kavalur in 1987 for the search of asteroids and other minor bodies in the solar system. A new asteroid numbered 4130 was discovered on 17 February 1988. This asteroid was later named Ramanujan after the Indian mathematical genius, Srinivasa Ramanujan.

Observations of occultation by solar system bodies have been carried out from VBO for almost a quarter century now and have yielded important results. Observations made at VBO contributed to the 1973 discovery of a thin atmosphere on the Jovian satellite Ganymede. Rings around the planet Uranus were discovered in 1977. Evidence for the suspected existence of an outer ring around Saturn was obtained in 1984. Mutual occultations of the Jovian satellites have been regularly observed since 1985. Analysis of these events has yielded improved ephemerides of the satellites and shown that the tides raised by Jupiter cause deceleration of satellite Io's mean motion. Mutual events of the Pluto–Charon system and lunar occultation of stars in optical and infrared for high angular resolution measurements are being regularly observed from VBO. From balloon-borne observations made by TIFR scientists on 10 December 1980, a reliable value of 97 ± 3.5K was obtained for the brightness temperature of Saturn's disc at 76–116 μm. It was concluded that the emissivity of the rings decreases substantially at far-infrared wavelengths.

Theoretical work on planetary atmospheres has been carried out at Osmania University, Hyderabad. Absorption and polarization line profiles were calculated for a semi-infinite planetary atmosphere in the integrated light as well as along the intensity equator and the mirror meridian for the Rayleigh phase matrix. Comparison with the observation of Venus revealed that the continuum originates in a deeper layer where Mie scattering predominates, while the lines arise in a higher layer where Rayleigh scattering prevails. A new definition of the effective depth of line formation was given, which explains the variation of the equivalent width over the disc, its inverse dependence on line strength and the phase effect in integrated light. H-functions were calculated for 35 anisotropic phase functions and used for studying the correlation between the phase function and the phase effect of the equivalent width.

Comets have received considerable attention. Imaging, photometric, spectroscopic, polarimetric and other observations of a number of comets have been carried out at various centres. During the occultation of the radio source 2025-15 by comet Kohoutek in January 1975, the Ooty Radio Telescope (ORT) was used to observe scintillations through the plasma tail. Halley's comet was observed in 1985–86 by various observatories as part of the International Halley Watch Programme. PRL scientists observed that comet Austin (1990) was richer in fine particles than comet Halley. Imaging of the nucleus of comet Swift-Tuttle (1992) at VBO showed that it had a rotation period of about three days. Multi-fragment crash of comet (1993c) Shoemaker-Levy 9 into Jupiter was observed during 16–22 July 1994 from Kavalur, Japal–Rangapur and Bangalore at optical, infrared and radio frequencies. Observing with the 10.4-m aperture millimetre-wave telescope, RRI astronomers recorded that every time a cometary fragment hit Jupiter, its radio emission at 86 GHz went up substantially for a short time. An intense infrared flash in the H-band caused by the impact of fragment S was detected on 21 July 1994 through the 0.75-m aperture telescope at Kavalur.

Meteoric activity at the Hyderabad latitude has been studied using a 50-MHz continuous-wave meteor radar during 1983–92 at JRO. The group working at PRL came up with valuable evidence from the analysis of meteoritic data on the early history of the solar system, including a signature of the active early phase of the Sun and isotopic records of ambient stellar nucleosynthesis. Significant results have been obtained on the total electron content of the ionosphere and the amplitude scintillations of the satellite radio beacon signals recorded at Hyderabad. Ionospheric irregularities have been studied at JRO by recording the Faraday rotation angles, using the three-station method, under the International Atmospheric Programme. An important result was obtained in 1969 on the effect of celestial X-ray sources on Earth's atmosphere while recording field strengths at Ahmedabad of 164 KHz radio waves transmitted from Tashkent. It was noted that a pronounced minimum recurred night after night during April–July. This phenomenon was attributed to increased ionization in the lower D-region of the ionosphere due to transit of SCO–1 across 71° E, the one-hop reflection meridian of radio waves from Tashkent to Ahmedabad.

STARS AND THE GALAXY

The Milky Way galaxy and its constituents have been extensively studied from ground-based observatories.

Classification of Am stars on the basis of their MK spectral morphology has been carried out using the Meinel spectrograph at the Nasmyth focus of the JRO 1.2-m telescope. As many as 100 spectra of Am stars and MK standards were obtained at 66 Å mm^{-1}, and their digital profiles used for classification. Using spectra at a higher dispersion of 33 Å mm^{-1}, Osmania University astronomers have detected a phase-modulated spectral line variation in some of these Am stars.

A study of chemical composition of classical Cepheids and related chemical inhomogeneities of the galactic disc was carried out from VBO. The [Fe/H] index of nearly two dozen Cepheids was derived. The places of formation of the Cepheids were determined by numerically integrating their orbits backwards in time under the influence of the axisymmetric and spiral-like gravitational field of the galaxy. A steeper variation of [Fe/H] across the Sagittarius and Perseus arms was encountered as distinct from the overall variation of [Fe/H] across the disc. Spectroscopic work on Cepheids has continued and chemical abundances in a number of them have been derived with the help of synthetic spectra.

Photometry and polarimetry of a number of hydrogen-deficient stars and carbon stars in UBVRI and JKHL bands have been done at VBO. Several R CrB variables have been followed in their deep minima and also during the recovery phase. Spectroscopy in the visible region has been combined with extensive IUE data to determine their atmospheric properties, to obtain information on the circumstellar environments of these stars, and to estimate their chemical composition.

High-dispersion coude spectra of several supergiants of late G and early K spectral classes have been obtained at VBO. The blue asymmetry was attributed to the occurrence of chromospheric expansion of these stars eventually leading to mass loss. Detailed radiative transfer models were computed to match the Hα equivalent widths, obtaining in the process the density distribution in the chromosphere as well as the mass low rates. The infrared Ca II triplet lines have been surveyed in a large sample of dwarfs, subgiants, giants and supergiants with the aid of high-dispersion coude spectra. Sensitivity of the equivalent widths of these lines to gravity, effective temperature and metallicity has been investigated. These results are of great value in the studies of stellar populations in galaxies.

Observation of SiO masers in red supergiants, in particular the Mira variables, has been a major programme with the millimetre-wave telescope at RRI. The study of cometary globules and their kinematics near OB associations (such as the Gum Nebula, Orion, Cepheus, and so on) is one of the major ongoing programmes with this telescope.

Polarimetric studies of individual stars have been carried out at VBO. Of particular interest have been the post-asymptotic giant branch stars with circumstellar dust shells. The RV Tauri star AR Puppis has been found to show very high linear polarization, $\approx$ 14 per cent, in the U band. This is the highest polarization observed for a single star not associated with a known nebulosity. In addition, pre-main sequence stars have been studied polarimetrically. Polarization maps of young OB associations and molecular clouds have also been obtained from VBO by IIA astronomers.

A detailed spectroscopic study of the Scorpio–Centaurus association was undertaken at VBO. Rotational velocities of the members of the association down to 8.5 mag were obtained. The study showed that the stars of the upper Scorpius group were fast rotators as distinct from those of the Centaurus–Lupus and lower Centaurus–Crux subsystems. The faster rotation of the upper Scropius group was attributed to either accretion effects or to effects of the interaction with the surrounding interstellar medium that might have partially destroyed the randomness of orientation. The data on Scorpio–Centaurus association were combined with the data on the other clusters to investigate the effects of rotation on colour indices of stars. A zero-rotation zero-age main sequence was determined following a conventional cluster-fitting procedure.

A possible evolution to the blue straggler phenomenon in open clusters in the spectral type domain of A stars was suggested, in which the anomalous position of these stars could be completely accounted for in terms of their slow rotation.

Star clusters have been studied at VBO for their intrinsic properties as testing laboratories of the theory of stellar evolution and from the point of view of galactic studies to discern if they showed a spiral pattern. A few of them containing astrophysically interesting objects like planetary nebulae have been observed in great detail to faint magnitudes. Star clusters have also been utilized to calibrate and standardize the photometry done at VBO.

An important contribution from VBO has been a detailed photometric study of the globular cluster Omega Centauri. Photoelectric scans were made along the major and minor axes in UBVRI. In addition, equidensity contours were obtained from direct photographs taken with an f/6 camera in BVI. Using these, the change of ellipticity from the centre to the outer regions of the cluster was evaluated. A large concentration of blue stars was discovered at a distance of 2.5–5.5 arcmin from the centre. Their distribution was elliptical in contrast to the more spherical distribution of red stars. Blue bulges were also observed in some other globular clusters.

Using the Fabry–Perot spectrometer of PRL, the IIA astronomers have carried out kinematic studies of planetary nebulae. Several bipolar nebulae and a few others with peculiar characteristics have been studied. Deep charge-coupled device (CCD) imaging of planetary nebulae in and away from the emission lines has been done in an attempt to discover the undetected nuclei. Colour excess maps of many of these nebulae have been prepared using broadband imaging. Particular attention was paid to M4-18, prototype of a class of planetary nebulae with WC 11 type central stars. These observations were combined with IUE and infra-red astronomy satellite (IRAS) data to study the properties of the star and the nebula.

Binary stars have figured prominently on the observers' agenda. The elements of Gamma Velorum determined from Kodaikanal in 1963 remained the most accurate for almost two decades. Another star that received a good deal of attention in the early days of VBO was Canopus. High dispersion (2.8 Å mm^{-1}) plates of this star were obtained in the blue region to study the variation of its Ca II K line profile.

Photometric and spectroscopic studies of RS CVn binaries have been perused at VBO for many years. In addition to accurate period determinations, detailed modelling has been done of the spots on a number of these stars (e.g., DM Uma, II Peg and V711 Tau). Be stars and Be X-ray binaries have been examined spectroscopically. Rapid variability in the Hα line profiles in a number of them has been closely monitored. VBO has participated in the international MUSICOS campaign on some Herbig Ae/Be stars and the Delta Scuti star θ^2 Tau.

UBV photometry of eclipsing binaries and variable stars has been an ongoing research project of long standing at Nainital. Mass, dimensions and physical properties have been determined for a number of eclipsing binary stars. In addition, period studies have been done for a few of them as well as for Delta Scuti, Beta CMa and RR Lyr stars. Gravitational radiation studies of eclipsing binaries are also being carried out.

A number of eclipsing have been observed in UBV passbands by Osmania University astronomers using their 1.2-m telescope at Japal–Rangapur. The secondary components of the Algols have been found to be not only over luminous but also hotter for their mass, indicating partial loss of their hydrogen envelopes. Improved periods have been obtained for four binaries. Period changes were studied for 23 systems, several of which were found to be triple systems. Two new variables have been discovered from JRO. Infrared photometry of Beta Cephei-, Delta Scuti-, Be- and RS CVn-type stars was also carried out. Optical counterparts of some X-ray binaries have also been studied in collaboration with X-ray astronomers from TIFR.

ISAC has developed photometers for observing the optical counterparts of X-ray sources. These observations have been carried out in collaboration with IIA. A 14-inch aperture telescope was installed in the ISRO campus in Bangalore. A two-channel star and sky photometer has been used to observe chromospherically active stars such as HR 1099, UX Ari, IL Hya, DM Uma and DH Leo.

In April 1979, the PRL and the TIFR scientists working at Kavalur reported detection of infrared bursts from an X-ray burster. The discovery was confirmed six months later by British astronomers at Tenerife. However, no bursts have subsequently been reported from the source.

ISAC has participated in an international campaign called the Whole Earth Telescope (WET) project in which the same white dwarfs are observed using similar instrumentation from different longitudes to produce continuous coverage of data for astroseismological studies. The white dwarf PG 1159-035 has been shown to have a mass 0.586 times that of the Sun, a rotation period of 1.38 days and a magnetic field of less than 6000 gauss. The twin white dwarf system AM CVn, earlier observed from Kavalur and Nainital, was also observed in March 1990 by the WET project. Analysis of composite data shows that the 1051s period decreases at a rate of $(3.7 \pm 0.4) \times 10^{-12}$ ss^{-1}. In the case of the single DB white dwarf GD 358, a mass of 0.6 times that of the Sun is deducted. It is also suggested that the white dwarf has a very thin layer of helium.

Several classical and recurrent novae have been spectroscopically monitored from VBO during outburst and a few during quiescence. Spectroscopic differences and similarities between individual novae in outburst have been studied and the physical parameters of the ejected shell estimated. Evolution of their photospheric radii and temperature has also been monitored in a few cases. The results indicate the presence of a white dwarf in the recurrent nova RS Oph for which alternative models exist that do not invoke a white dwarf. The accretion disc spectrum has been estimated from the observations of novae in quiescence and mass transfer rates, and geometrical parameters of these discs derived. Spectroscopic monitoring of T CrB over a long base line in time has shown secular as well as orbital phase-dependent variation in emission line strengths. Using the images of the shell of GK Per, the proper motion of individual knots has been measured and the velocity deceleration derived. Astronomers at PRL have observed dust formation as early as seven days after eruption in the fast Nova Her 1991. The result is rather surprising because fast novae generally do not produce substantial amounts of dust. ISAC scientists have measured UBV magnitudes of Nova Cygni 1992. Polarimetric studies of the peculiar symbiotic system R Aquarii by PRL scientists have suggested the existence of a processing jet. Line profile studies in Hα give evidence of an expanding shell with a velocity of about 15 km sec^{-1}.

Eight pulsars have been discovered by NCRA astronomers using the ORT. Simultaneous observations of a few pulsars at 327 MHz from Ooty and the Parkes Radio Telescope in Australia revealed the existence of multiple diffracting plasma screens in interstellar medium in some directions. Subsequently, an analysis of the spatial distribution of a large sample of pulsars from the Molonglo survey was used to infer the presence of a high-electron density layer about 150 light years below the plane of the Galaxy.

RRI astronomers have carried out radio observations at 12 cm mainly with the Parkes interferometer, the VLA and the 26-m antenna at Hobart. The scientific objectives of these studies are: (i) to understand better the velocity distribution of interstellar clouds, (ii) to get a handle on their scale sizes, and (iii) to measure distances to pulsars. An important project undertaken with the low-frequency array at Gauribidanur was an all-sky survey at 34.5 MHz, using the method of one-dimensional image synthesis.

The low-frequency array at Gauribidanur was used by the RRI scientists to study the characteristics of pulsed emission from about a dozen pulsars. The study includes: (i) a detailed analysis of their pulse profiles, (ii) interpulse emission, (iii) fluctuation spectra, and (iv) slow variability. Currently, a deep survey is underway with the ORT.

The radio jet in the Crab nebula has been extensively investigated. A joint Indo-Japanese experiment to study the occultation of the Crab nebula by the moon in January 1975 revealed that the area emitting diffuse hard X-rays is significantly smaller than that emitting soft X-rays. This is consistent with the synchrotron origin of X-rays. Observations of CTB 80 were among the first to reveal its peculiar structure. It has a small-diameter (1 arcmin) core, extended ridges (size about 1°), X-ray point source and an embedded pulsar of 30-cm period.

The non-thermal radio source G18.95-1.1 was shown from Ooty Synthesis Radio Telescope (OSRT) observations to be a shell-type supernova remnant (SNR) with a central source perhaps similar to the accreting binary SS433. It has been shown that in the case of G25.5 + 0.2 (which was earlier believed to be the youngest SNR in our Galaxy), the observed emission actually arises from stellar outflow from what is perhaps the most massive star in the Galaxy.

A lunar occultation of the radio source Sgr A, associated with the centre of our Galaxy, was observed by NCRA astronomers from Ooty in September 1970. With a resolution of about 1 arcmin at 327 MHz, the observations of Sgr A provided the first details of its synchrotron radiation revealing a multi-component structure superimposed on a halo with a diameter of about 20 pc. Attempts were made to determine the abundance of deuterium by looking for the deuterium absorption line at 327.4 MHz in the direction of the Galactic centre with ORT. These studies have provided the best upper limits on the D/H ratio by the radio technique.

About half a degree area of the Eta Carina nebula was mapped in 1983 by the TIFR scientists in 120–300-micron band, using a balloon-borne 100-cm telescope. About 30 compact sources were detected, many of which do not find counterparts in the IRAS catalogue. Only a few per cent of the total luminosity of OB stars in the region is radiated in the far-infrared in contrast to young H II regions where most of the energy is emitted in the far-infrared. The young H II region complex W 31 was mapped in the 120–300 micron band as well as in the radio bands. Eight new infrared sources were detected. It was also shown that the region is short of high mass, high luminosity stars. Other H II region-molecular cloud complexes with deeply embedded sources have been studied in detail.

NCRA astronomers have made wide-field radio maps of the bright nearby H II regions Orion A and B. The observations have been made at two wavelengths: 90 cm, where the central regions are highly opaque, and at 2.8 cm, where the nebulae are fully transparent. These studies have yielded the most accurate estimates of the electron temperatures of these nebulae from radio continuum data alone.

An extensive survey of hydrogen recombination lines in the galactic plane has been carried out by the RRI astronomers using ORT. Results include discovery of large low-density envelopes around the conventional H II regions. Radio recombination lines have been systematically observed by the RRI scientists over a wide-range of frequencies (25 MHz to 10 GHz) from a variety of objects such as H II regions, cold interstellar clouds, the warm ionized interstellar medium, the galactic centre, nuclei of external galaxies, and so on. These observations done with the ORT, the low-frequency array at Gauribidanur, the 43-m and the 93-m single-dish telescopes of the National Radio Astronomy Observatory, as well as the VLA (very large array), have been used to derive some of the properties of different ionized regions.

To study the properties of the ionized component of the interstellar medium, an extensive interplanetary scintillition survey of the galactic plane was carried out by the NCRA scientists using ORT. The absence of sources with components smaller than 0.5 arcsec in the galactic central region indicates large interstellar scattering in these directions. A two-component model for the distribution of scattering plasma and an estimate for the scattering angle as a function of latitude were also derived from these observations.

A major research interest at IIA has been radiative transfer studies including computation of intensity and polarization line profiles in the spectra of planetary atmosphere; and studies of line formation in extended and moving atmospheres. Scientists from TIFR have proposed the idea of pressure dissociation in the context of stellar atmospheres and estimated its effect. TIFR scientists have discovered CO molecules in hot B supergiants and several Be stars. Cosmic ray excitation of the

Lyman and Werner systems of the hydrogen molecules has been shown by the TIFR scientists to produce chemically significant levels of ultraviolet (UV) photon flux in dense clouds. Dynamic models of the formation of low-mass stars from interstellar clouds incorporating processes such as excitation, ionization, cooling and chemical reactions have been constructed by the TIFR scientists. Scientists from IUCAA have been working on models of stellar and primordial nucleosynthesis and their relationship to the observed abundances and the overall chemical evolution of the Galaxy. Theoretical studies of pulsars are being carried out at various centres include RRI.

Artificial neural networks (ANNs) are computer-based statistical tools for the classification of various patterns (like electrical and other communications-type signals, images, etc.) and for the prediction of time-series type applications like EEG patterns of epileptic patients or earthquake predictions based on previous data, and so on. In the recent decade, ANNs have entered the field of astronomical applications due to the increasing demand on the large databases, which are upcoming as a result of new satellite-based large surveys. The ANNs though known in the early 1960s–1970s, were limited to the available computation power in those days. With the advent of more powerful computers that can handle very large database, there has been renewed interest in ANNs and their applications. The group at IUCAA has made pioneering efforts in applying ANN to the classification of stellar spectra (spectrum is the distribution of light intensity versus wavelengths) right from UV to optical to infrared (IR). In a recent joint collaboration with teams from the USA, they have completed a large stellar spectral library of about 1,200 stars to which ANN has been applied successfully. Further, with a Canadian team, they have classified 2,000 IR spectra using ANNs to accuracies better than 85 per cent.

GALAXIES AND COSMOLOGY

Improvements in techniques have made it possible to study other galaxies in depth. At IUCAA, work on photometry of galaxies and their morphology has progressed with empirical modelling going hand in hand with observations, some of them carried at international facilities. Work at IUCAA on quasar spectra and related issues like the ambient state of intergalactic medium and radiation background has also made a mark. For example, it has been possible to argue from such data that at redshifts of $z \sim 2$–3, the temperature of the cosmic microwave background was consistent with $(1 + z)$ times the present temperature.

A photographic study of 50 Sersic-Pastoriza galaxies was carried out at IIA using the Kavalur 1-m reflector. Nuclear regions of these galaxies show bright substructure due to episodes of star formation. A classification scheme was suggested that reflects the intensity and evolutionary stage of the star burst. The nuclear components of sizes less than 1 kpc were distinguished from circumnuclear components of mean size 1.5 kpc. The nucleus is often very red, and was identified for the first time in NGC2903 using high-resolution I-band images. The brightness of the nuclear and circumnuclear components in the barred galaxies in the sample has been correlated with the length of the bar indicating the role of the bar plays in the supply of gas to the centre.

A survey of red stars in the direction of large magellanic cloud (LMC) has been completed at IIA, using ultra-low resolution objective prism spectra taken at the 1-m reflector. A majority of the stars are M giants and supergiants or carbon stars belonging to the LMC. BVR Hα photometry has been carried out from VBO for 161 H II regions in nine galaxies. Specific model spectra have been constructed with a view to interpreting these observations. Comparison of the two reveals the following: (i) The stellar component experiences lesser amount of dust extinction compared to the gaseous components. There is also evidence for a significant escape of ionizing photons from the brightest regions. Both these observations indicate a clumpy distribution of the gas. (ii) A majority of regions have undergone more than one burst of star formation during the last 10 million years. (iii) About 10 solar masses of gas is converted into stars during each burst of stars formation. IIA astronomers in collaboration with scientists from TIFR and IUCAA have observed early-type galaxies that are members of small groups, selecting them for their radio or X-ray brightness. A majority of galaxies observed have shown evidence of gas and dust. Studies of surface brightness of galaxies in various colours, star-forming regions in galaxies and variability of quasi-stellar objects (QSOs) and active galactic nuclei (AGN) are some of the programmes that are being pursued in the field of extragalactic research by scientists from IIA, IUCAA and TIFR.

Over a dozen extragalactic supernovae have been observed spectroscopically near light maximum from VBO and their spectral type and their expansion velocity determined. A few of these, notably SN 1987A in LMC and SN 1993J in M81, were monitored for longer periods. SN 1987A was a subluminous type II and exploded after the progenitor had made an excursion towards blue in the H-R diagram following a red supergiant phase. Astronomers of IIA have produced evidence indicating nitrogen enrichment in the surface layers. This implies CNO cycle processing in the progenitor. The velocity structure of the outer layers was measured for both these supernovae, and a distance estimate obtained for SN 1993J.

IIA astronomers have contributed to the International Active Galactic Nuclei Watch by monitoring NGC 3783 spectroscopically and photometrically. Search is also being made for intra-night optical variability in radio-quiet QSOs in order to constrain theoretical mechanisms for microvariability. Photometry has been performed on X-ray-selected AGN. At IIA, the population synthesis technique has been applied to a few nearby galaxies using spectra obtained at the European Southern Observatory, Chile. The age of the older population and the epoch of recent star formation were determined for the galaxy NGC 5128. Other projects at IIA using data obtained elsewhere include the study of stellar content of young star cluster in the LMC.

Numerical and analytical studies in galaxy dynamics have been carried out at Osmania University, IIA, PRI and TIFR. Analytical results on tidally interacting galaxies using impulse and adiabatic approximations have been obtained at Osmania.

Numerical work at IIA has shown them to be in broad agreement with the N-body computer simulations in respect of merger velocities, energy transfer and merger times. Transfer of not only energy but also angular momentum in the case of tidal encounter between galaxies has been numerically investigated at IIA.

One of the major programmes carried out with the ORT has been a lunar occultation survey along the moon's path in the sky. The survey yielded accurate positions and brightness profiles for about 1,000 weak radio sources with resolutions of about 1–10 arcsec at 327 MHz. Such high resolutions had not previously been attained for any large sample of weak sources. The positional accuracy was sufficient to make reliable optical identifications on the Palomar Sky Survey prints. The database was used to establish, for the first time, a correlation between the angular sizes of the radio sources and flux densities, which in turn led to the important conclusion on the evolution in physical sizes with cosmic epoch. A significant fallout of the occultation programme was the development of a new technique of deconvolution of occultation records. This resulted in a two-fold improvement in the resolution achievable in obtaining brightness distributions over the conventional methods. It was one of the first uses of the positivity constraint as a priori information, which was later applied in the maximum entropy methods for deconvolving radio images obtained with aperture synthesis telescopes.

Another major programme undertaken with ORT has been the observations of interplanetary scintillations (IPS) in the intensity of distant radio sources. These scintillations are caused by electron-density irregularities in the interplanetary medium (solar wind). Such observations made at different solar elongations provided valuable information both on the properties of the medium and on fine structure (<0.5 arcsec) in radio sources. Scintillation studies of hundreds of sources lead to the conclusion that in the case of a large number of powerful radio sources, a significant fraction of their flux density arises in compact (<0.5 arcsec) hot spots in the outer lobes. More direct estimates of the angular sizes of hot spots in a sample of 3CR radio sources at large redshifts were subsequently obtained using very long baseline interferometry (VLBI) techniques, which showed that compact hot spots (sizes <0.15 arcsec) were fairly common in powerful radio galaxies and quasars. Detailed radio images of a large number of quasars at the VLA were also used to show that there is no significant dependence of the sizes of the hot spots on either redshifts or radio luminosity. The relative strength of the hot spot, however, appears to increase with radio luminosity.

That compact sources (with overall sizes <10 kpc) constitute a significant fraction of the population with steep radio spectra was first recognized from high-resolution observations with the Westerbork Array of a complete sample from a 5-GHz survey. Work by the NCRA scientists has shown that the fraction of such sources appears to increase rapidly with redshift, which could be related to an enhancement in the beam efficiency and to stronger confinement in a denser interstellar medium at earlier epochs.

Some of the earliest statistical tests to explore the possibility of a 'unification scheme' in which the flat-spectrum core-dominated sources are the relativistically beamed counterparts of the lobe-dominated ones were carried out at NCRA. Several properties such as projected linear sizes, hot spot misalignments, redshift distributions, orientation of radio polarization vectors, and so on, were found to support the unification scheme. Evidence was also presented for an aspect dependence of the optical/UV continuum emission of quasars, which implied that all optical magnitude-limited samples of radio quasars were likely to be biased with regard to the orientation of their jet axes. It now appears that both radio galaxies and quasars should be included in an enlarged unified scheme in which they are all intrinsically similar, but objects with small viewing angles (<450) are seen as quasars and those with larger viewing angles as radio galaxies.

The NCRA scientists have inferred hot spot velocities of about 0.1–0.25c in double radio sources on the assumption that the entire observed asymmetry is due to the fact that they are seen at different ages owing to light-travel-time effects. It has been recently shown that the closer of the two hot spots almost always lies on the same side of the nucleus in which the extended optical line emission has a higher surface brightness. This appears to provide the first direct evidence that lobe distance asymmetries could be largely intrinsic in nature. In quasars, the misalignment of the hot spots on the two sides have been found not to depend on the epoch.

A three-year flux monitoring programme at 327 MHz carried out using the OSRT has provided fresh support for an extrinsic origin (possibly due to refractive interstellar scintillations) of low-frequency variability in quasars. A superluminal microlensing model has been proposed to explain the phenomenon of ultra-rapid variations (with day-like timescales) at centimetre wavelengths. The bright pair 1830-21 of flat-spectrum radio components separated by just 1 arcsec was discovered serendipitously by NCRA scientists in the course of the Ooty Galactic Plane Survey, and has been interpreted as core of a distant radio source being lensed by an intervening galaxy. Later, VLA and Merlin maps revealed it to be a compact 'Einstein ring'. The giant radio galaxy 0503-28 with a size of 2.5 Mpc, which is the largest known radio source in the southern hemisphere, was discovered by the NCRA scientists independently from observations with the OSRT and using the Molonglo Synthesis Telescope in Australia. As part of an extensive study of clusters of galaxies, an ultra-steep spectrum radio source without any obvious optical counterpart was discovered in the cluster Abell 85 by the NCRA scientists.

The NCRA scientists have used the OSRT to study the large-scale structure of a number of nearby galaxies. A multi-frequency study of the edge-on spiral galaxy NGC 4631 showed evidence of spectral steepening with distance from the disc of the galaxy. A number of Seyfert and Sersic-Pastoriza galaxies have been studied with high angular resolution using VLA and Merlin arrays to look for radio evidences of starbursts and collimated ejection from their active galactic nuclei. Several studies have been made by the NCRA scientists and collaborators to determine the local and evolving radio luminosity functions and on possible explanations for the observed changes. Spectral measurements of the Ooty occultation sources, combined with several other datasets, have been used to establish a statistical relation between median radio spectral indices and flux densities of extragalactic sources found in metre-wavelength surveys. These studies have raised doubts about the long-held view that the average spectral index was steeper at earlier epochs.

The TIFR group is closely involved in two major programmes to optically identify and study high redshift galaxies from Molonglo and Ooty samples. These studies led to the discovery of about 25 radio galaxies at redshifts greater than two, including two at $z > 3$, which were then among the most distant galaxies known in the universe. Observations with the ORT have allowed interesting upper limits to be placed on the H I mass of the clusters and superclusters at $z = 3.3$. As already noted, it would be possible to undertake much more sensitive searches for H I at even higher redshifts, using the GMRT. Using the Australia Telescope at a frequency of 8.7 GHz, scientists at NCRA and Australia placed an upper limit of 2×10^{-5} fluctuations in the cosmic microwave background radiation on an angular scale of about 1 arcmin. This was at the time the most stringent upper limit on fluctuations on this scale.

It was shown by TIFR scientists that the Seyfert galaxy NGC 4945 is quite extended at all IRAS bands, while another Seyfert, Circinus galaxy, shows only central emission. It was also found that the extended emission from NGC 4945 at 26 K is cooler than the central emission at 39 K.

Work on structure formation in the Big Bang model and its development through computer N-body techniques was initiated in TIFR and later continued in IUCAA with the result that India has become recognized as a strong player in this field. Following the lead of Fred Hoyle who consistently opposed the Big Bang scenario, there have been works on alternative cosmologies followed in India at IUCAA, mainly the quasi-steady state cosmology that was proposed in 1993 by Hoyle, Geoffrey Burbidge and Jayant Narlikar. In this context, it is worth stressing the fact that the peer review of the system for funds has not operated as rigidly in India as in the West. This has resulted in some papers of the non-conformist kind appearing from India in reputed international journals. Thus, it is still possible in Indian institutions to do research on alternatives to the Big Bang cosmology or to question the cosmological hypothesis for quasar redshifts.

IUCAA has also made a mark in the area of gravitational-waves data analysis, with several workers trained here now being absorbed in the world's limited but small community of scientists working on the state-of-the-art detectors of gravitational waves. The first elusive signal is still a long way away, but to catch it one needs very sophisticated techniques of analysing the data collected by these detectors.

SPACE AND HIGH-ENERGY ASTROPHYSICS

Strictly speaking, the discussion in this section should have been distributed between the two preceding sections. However, for the sake of convenience, results of X-ray and gamma-ray observations have been grouped here.

In the early phase, the key objective of the hard X-ray astronomy programme at TIFR was a detailed study of spectral and temporal characteristics of known sources like Sco X-1, Cyg X-1, Her X-1, X-3 and sources towards the galactic centre. Simultaneous hard X-ray and optical observations of Sco X-1 during 1968–72 showed that the X-ray intensity in the 20–40 keV range shows positive correlation with the optical luminosity in the bright phase of Sco X-1. It was also concluded that a flare results from an increase in the total mass of the hot plasma but not its temperature. In 1984, a temperature of $kT = 6.5 \pm 0.9$ keV was deduced from Sco X-1 X-ray spectra using a thermal bremsstrahlung model. In 1971, Cyg X-1 was shown by the TIFR scientists to be one of the most chaotic and rapidly varying sources at all X-ray energies. A hard X-ray flare was reported for the first time (subsequently verified by the PRL group and others). The 1984 observations implied a Comptonized black-body spectrum with a plasma electron temperature $kT = 28 \pm 4$ keV. No evidence was found for any kind of pulsed emission, thus ruling out an embedded pulsar in Sco X-1.

The star of 1973 was the binary Her X-1. Its spectral measurements were extended to 60 keV. It was shown that the pulsed component was less than 10 per cent of the total emission in hard X-rays. This result was later borne out by satellite measurements. It was also shown that the origin of the low- and high-energy X-rays must necessarily be the same. The source 4U1907 + 09 showed (in 1985) only marginal pulsations with a period of 432.70 seconds in the 20–80 keV interval. This result, however, needs to be confirmed. The 1984 observations of the X-ray pulsar GX1+4 seemed to imply a reversal of the spin-up of the embedded neutron star.

Rocket-borne X-ray observations have been made in the 0.1–20 keV range of a number of objects: Transient sources like Cen X-1, Cen X-2 and Cen X-3, binary sources like Sco X-1 and Cir X-1, supernova remnants as well as the diffuse X-ray background. Balloon-borne observations in the energy range of 20–200 keV have been carried out for a number of sources including Her X-1 and Cyg X-1.

The first Indian satellite, Aryabhata, carried a payload consisting of X-ray telescopes in the medium energy 2–20 keV and the hard range 20–150 keV. An X-ray sky monitor camera (designed and built in collaboration with TIFR) was placed on the Bhaskara I satellite. Those pioneering efforts have now matured to make the Astrosat, which will have an X-ray astronomy experiment (in collaboration with TIFR) and an ultraviolet detector (through collaboration at IUCAA and IIA) to be launched as a satellite by ISRO.

An experiment for studying celestial gamma-ray bursts was set up by ISRO aboard SROSS-C satellite launched on 20 May 1992. The experiment was aimed at measuring the temporal and spectral evolution in the gamma-ray bursts in the energy range 20 keV–3 MeV. The experiment worked satisfactorily during the satellite's short lifetime of 54 days. Another experiment for gamma-ray studies is a part of payloads of SROSS-C2 launched on 4 May 1994. An experiment was carried out by the TIFR scientists to measure the diffuse gamma-ray background in 0.2–4 MeV energy range. It was concluded that the emission is of extra-galactic origin. The observed spectrum is well accounted for by a power law spectrum of index -1.8 ± 0.2. A series of balloons were flown during 1977–80 in collaboration with scientists from Moscow. It has been shown that in the case of the Seyfert galaxy 3C120, gamma-ray luminosity exceeds the X-ray luminosity by a factor of 100.

Scientists from TIFR and Bhabha Atomic Research Centre (BARC), Bombay have studied high-energy gamma rays using the atmospheric Cherenkov arrays at Pachmarhi and Gulmarg, and the air shower arrays at Kolar Gold Fields (KGF) and Ooty. Highlight of results obtained during 1984–94 is that some objects like the Crab pulsar and Hercules X-1 are sporadic emitters of gamma rays. In 1987, pulsed gamma-ray emission was detected from the radio pulsar 0355 + 54, from Pachmarhi, in confirmation of theoretical predictions. That white dwarfs, such as neutron stars, could also produce pulsed emission was shown by Gulmarg observations of the cataclysmic variable AM Herculis. In various collaborative programmes, data from satellites have been analysed. In addition, there have been related theoretical studies.

The TIFR scientists have measured the low but finite fluxes of Li, Be and B in the primary cosmic radiation allowing one to deduce the path lengths of primary cosmic rays. Measurements were made of the electron and positron energy spectra in primary cosmic rays up to a few tens of GeV energies, with a view to understanding some aspects of acceleration and propagation of primary cosmic rays. A qualitative estimate has been made of the charge composition of primary cosmic rays in the energy range 5×10^{14} to 5×10^{16} eV by simultaneous observations on electrons at the surface and on muons underground at the KGF in extensive air shower experiments.

GENERAL RELATIVITY AND GRAVITATION

Work in the 1940s and 1950s included well-known contributions by P. C. Vaidya (1943) and A. K. Raychaudhuri (1955).[3] Vaidya had shown how to describe the space-time geometry and gravitational field of a radiating star. This solution became very important for astrophysicists when they discovered quasars, highly compact but very powerful sources of energy. Raychaudhuri's equation became the starting point for general relativists to study gravitational collapse of a massive object or of the entire universe. Thus, important work on space-time singularity arising in such cases followed in the decade of 1960s.

By and large, work in general relativity in India has involved solving differential equations to find exact solutions of Einstein's equations and studying some geometrical aspects of the theory. This work is being carried out at various centres including colleges and universities. There have been some important contributions to gravitation theory and cosmology, including studies of black holes.

The perturbations of black holes in normal as well as in quasi-normal modes have been studied at RRI, IUCAA and IIA. The scalar perturbations of spherically symmetric black hole solutions in theories with quadratic Gauss–Bonnet corrections have also been investigated. Charged particle trajectories around black holes in vacuum as well as magnetic fields have been studied by several authors at PRL, IUCAA, Indore and Ravishankar universities. It has been shown at IUCAA that the criterion for corotation should be redefined relative to a locally non-rotating observer so as to avoid conflict with the second law of black hole physics and the conservation of energy. An attempt was made at TIFR to define a black hole in an expanding universe. Workers at IUCAA and the University of Poona have considered the effect of rotation and magnetic field on the shape of the event horizon of a black hole. In the spirit of the Gauss theorem, the gravitational charge of a rotating black hole has been defined and applied to a black hole in a magnetic field.

Modern techniques have been employed at TIFR to study the type of matter distribution in the physical universe that is allowed by general considerations of global hyperbolicity and causality. Quantum effects on space-time singularities of general globally hyperbolic space-times have been investigated at TIFR, leading to the conclusion that some non-singular states are also probable. Linearization stability of the solutions of Einstein's equations has been demonstrated by workers from TIFR and Bhavnagar and Nagpur universities. Works on the extent of validity of the cosmic censorship hypothesis is going on at TIFR and Aligarh Muslim University.

Scientists at IUCAA and TIFR have done pioneering work in the area of quantum gravity by quantizing the conformal degree of freedom and studying its cosmological effects. In this restricted treatment, it is shown that quantum effects will force the universe to avoid the Big Bang singularity. Quantum field theory (QFT), in curved space-time, semiclassical calculations in space-times of interest and the application of results from particle theory to cosmology including inflation have been considered by several workers.

The existence and relevance of dark matter in astrophysics and cosmology was first published in 1972 in a collaborative study from TIFR.[4] The proposal was that weakly interacting particles with a finite rest mass (neutrinos) left over from the Big Bang would constitute a gravitating background of invisible matter; these would trigger the formation of galaxies and would explain the discrepancy in the viral masses of Galactic systems. In the mid-1980s, there was a spurt of activity on this topic and several workers considered dark matter of various types. Cosmological implications of cosmic strings are being considered at TIFR and IUCAA. A major effort on data analysis of gravitational waves in various detecting systems is currently under way at IUCAA. The signal-to-noise analysis including the photon counting noise and thermal noise has been made for an array of five, four and three detectors.

The properties of a thin accretion disc around a rotating black hole in a magnetic field have been considered at PRL and Ravishankar University. The magnetohydrodynamics around rotating black holes has been extensively studied at TIFR. By taking into account the presence of magnetic field around a rotating black hole, scientists at IUCAA have revived the Penrose process of energy extraction as a viable mechanism for powering the central engine in active galactic nuclei and quasars. The capture of gravitational neutrinos has been extensively studied at RRI. Scientists at IIA and the University of Delhi have studied gravitational redshift and spectral line broadening of radiation from a rapidly rotating pulsar by taking the Kerr metric to represent the pulsar. A suggestion to consider the white holes as a source of high-energy radiation was also studied at TIFR, IIA and Poona University in the 1970s. The gravitational bending of a light ray gives rise to the astrophysically interesting phenomena of gravitational lensing and superluminal separation of VLBI components in quasars. Considerable work has been done in this important area at TIFR and RRI.

A CRITIQUE

We can single out three cosmic events from the past two centuries and use them as benchmarks in discussing the advent and growth of modern astronomy in India. The 1769 transit of Venus took place at a time when England and France were engaged in bitter rivalry over India. This brought positional astronomy in India as a navigational and geographical aid. The 1874 transit of Venus saw India firmly in British grip. The new science of physical astronomy was taking shape, and the British scientific activity was commensurate with its economic and political status.

Janssen, the French astronomer, observed the total solar eclipse from Guntur in 1868 and identified a spectral line that was new. He and his independent British co-discoverer Lockyer identified it with a new element that they named Helium because of its solar association. Helium was discovered in the laboratory much later. During his post-eclipse stay in Simla, Janssen made the first spectrohelioscope, which facilitated the daily observations of the Sun.

Solar physics came to India because the British astronomers wanted data from sunny India, and because the government was given to understand that a study of the Sun would help predict the status of monsoons. Interestingly, the work plan prepared by the Royal Society for Kodaikanal Observatory in 1901 makes no mention of the solar-terrestrial connection. By the time comet Halley appeared in 1910, India's new middle class had become politically assertive and scientifically ambitious. While the Indians on their own remained mere dabblers in observational astronomy, they made original contributions in the fields of theoretical astrophysics and relativity in which areas they no doubt felt more at home. This was how the situation was when the British left India.

Nevertheless, while the Indian's love affair with theory continued, the post-Independence renaissance of astronomy in India has seen a rise in the observational component too. Govind Swarup's pioneering work on radio telescopes in Ooty and then at Khodad (the GMRT), Vainu Bappu's leadership in optical astronomy, and the beginnings of space astronomy from TIFR and PRL along with the ISRO's achievements of launching satellites have lifted Indian observational astronomy from the routine observing of the Sun and the star to the more exciting studies in cosmology and high-energy astrophysics. A more encouraging aspect is the beginning of observational studies in the Indian universities, thanks to IUCAA's help and directions. It is thus possible for an astronomer from Raipur to carry out observations of galaxies on an 8-m class international telescope in Chile. No less creditable is the Indian enterprise of placing a 2-m telescope at the world's highest site, at Han Le in Ladakh, some 4,500 m above sea level. Set up by IIA, the telescope can be used by remote control from near Bangalore more than 2,000 km.

However, there are reasons to worry too! The number of bright young students attracted to pure sciences, including astronomy, is fast dwindling and one feels that even the existing observing facilities may remain undersubscribed if this trend continues. Although institutions like IUCAA are attempting to recreate the interest in basic science in schools and colleges, there is need for more scientists to get down to the students and share with them the excitement of doing science.

NOTES AND REFERENCES

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2. B. Datt, *Zeitschrift für Physik*, **108**, 1938: 314.
3. These papers describe the key features of the work done by Vaidya and Raychaudhuri: P. C. Vaidya, 'The External Field of a Radiating Star in General Relativity', *Curr. Sci.*, **12**, 1943: 183; and A. K. Raychaudhuri, 'Relativistic Cosmology I', *Phys. Rev.*, **98**, 1955: 1123.
4. This work was by R. Coswik and J. McCleland, titled 'An Upper Limit on the Neutrino Rest Mass', *Phys. Rev. Lett.*, **29**, 1972: 669.