13 ASTRONOMY IN INDIA IN THE 20th CENTURY

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ASTRONOMICAL STUDIES IN INDIA

Interest in astronomy dominated Indian thinking from the very early times. Many references to astronomical events and their interpretations are found in the Hindu, Jain and Buddhist Scriptures. During the period of compositions of astronomical *siddhāntas* (5th to 12th century A.D.) the motions of the Sun, Moon and planets were studied in detail. It is well known that Āryabhaṭa, Varāhamihira, Brahmagupta, Bhāskara I and Bhāskara II made monumental contributions towards the development of astronomy. These early astronomers whose contributions have been discussed in detail in the previous chapters, had influenced the academic endeavours for several centuries. This was followed by a period of relative inactivity till late seventeenth century.

In the year 1609 the optical telescope was discovered in the western world and its extensive use by Galileo revolutionized the study of astronomy. The first major development in new astronomy in India occurred when Father Richaud, a French Jesuit priest used the astronomical telescope for the first time on the Indian soil in the year 1689. He discovered a comet and the binary nature of the bright star alpha Centauri from Pondicherry.[1 2 3] Next important landmark was the work of Raja Jai Singh (1686-1734). He launched an ambitious programme of development of observational astronomy by establishing a chain of 5 observatories at Delhi, Jaipur, Mathura, Ujjain and Varanasi and started accurate observations. These institutions contained enormous masonary instruments many of which were invented by Jai Singh himself. Magnificent in concept, in practice they had little use. It is still a mystery why Raja Jai Singh did not use telescopes extensively instead of the huge cumbersome masonary structures, since some recent studies have shown that Raja Jai Singh was familiar with telescopes and had even incorporated telescopic observations in the compilation of astronomical tables,[4 5 6] The first modern observatory was established in Madras by the British East India Company in 1792. "The East India Company having resolved to establish an observatory at Madras for promoting the knowledge of astronomy, geography and navigation in India, Sir Charles Oakely, then president of the Council, had the building for the Observatory completed in 1792". The first observations were commenced in 1787, through the efforts of William Petrie who had with him two 3″ achromatic telescopes, two astronomical clocks and an excellent transit instrument. This equipment formed the nucleus of the instrumentation of the new observatory which soon embarked upon a series of observations of stars, the Moon and eclipses of the Jupiter's satellites.[7 8 9] For over a century Madras Observatory made systematic measurements of stellar positions and brightness. Goldingham, Taylor, Jacob and Pogson were government astronomers, who dominated the activity. J. Goldingham was the first astronomer at Madras. His earliest observations made in 1793 were recorded in a manuscript volume where an account of the observatory building was also given. Further observations were published by him in later volumes in 1812 and 1825.[10 11] Taylor completed in 1844 his catalogue of places of over 11,000 stars. [7 12] Jacob's principal interest was double stars, viz. measures of their separation and determination of their orbits. [7 13] From 1861 until his death in 1891, N. R. Pogson entered newer areas of observations. With the help of an 8-inch Cooke equatorial he made discoveries of asteroids and variable stars. [16] Pogson also undertook the preparation of a catalogue and atlas of variable stars complete with magnitude estimates.[14 15] These were edited by Turner after Pogson's death. The discovery in 1867 of the light variation of R Reticuli by C. Raghunathachary is perhaps the first astronomical discovery by an Indian in recent history. [8 17]

After Jai Singh, the Royal patronage for astronomical efforts was taken over in several Indian states in the 19th and early 20th century. The King of Oudh had established an observatory at Lucknow around 1932. The principal equipment here was a mural circle of 6 ft, a 8 ft transit instrument and an equatorial telescope by Troughton and Simms. Wilcox who assumed charge of the observatory made some observations but after his death the observatory was closed down in 1849.

In 1837, the Maharaja of Travancore had founded an observatory in Travancore. It had a transit instrument, two mural circles and an equatorial telescope and magnetic and meteorological instruments. The observatory was, however, wellknown for magnetic observations made by Broun who was the Director from 1851 to 1865. His chief discovery is now hailed as one of the fundamental principles of terrestrial magnetism, that magnetic disturbances on earth are not localized but are a world-wide phenomenon.[8] Broun is also associated with the discovery of the relationship between solar disturbances and subsequent changes in the state of the earth's magnetism in recurrent intervals of 27 days. After Broun's retirement the activity of the observatory was greatly reduced.

Special mention must be made of the observatory started in Poona in the last decade of the 19th century. This was the Maharaja Takhtasinghji Observatory which functioned on modern lines. It commenced work under the direction of K. D. Naegamvala, part of the funds for this observatory coming from the Maharaja of Bhavnagar. The observatory had the largest telescope in the country, a 20″ Grubb reflector.[9 19] The most important work that appeared from this observatory was the observation of solar corona during the total solar eclipse of 1898. The Naegamvala expedition of Jeur and the observation of corona and its spectrum are described in Vol. 1 of the publications of Maharaja Takhtasinghji Observatory.[20] The observatory was closed down in 1912 and the 20-inch reflecting telescope was transferred to Kodaikanal Observatory. [21]

There were three total eclipses with paths of totality across India during the 19th century. The first eclipse was in 1868, the observation of which resulted in astrophysical work of great importance. It was the French astronomer Janssen who, stationed at Guntur in Madras Presidency, applied the spectroscope to the Sun during the moments of totality.[22] [23] He found a spectral line close to and on the blue side of the yellow lines of sodium. This was the first eclipse to be observed with the spectroscope. The hydrogen emission lines seen were so strong that Janssen reasoned that could be seen even without an eclipse. Next day he observed again and the bright lines were there just as he had predicted.[14] There were several eclipse teams scattered over the path. The Madras Observatory had two teams one at Vanpurthy and the other at Maslipatnam where Pogson was in charge. The English expedition was led by J. F. Tennant at Guntur who also made the discovery of the D3 line.[25] Sir Norman Lockeyer attributed the line to a hitherto unknown element christened as "helium". Helium was discovered in the laboratory 27 years later by Ramsey.[24]

The eclipse of 1871 had a path of totality passing over Ootacamund and Pudukotai near the southern tip of the country. Janssen, at this eclipse, reported the discovery of dark absorption lines in the coronal spectrum. This was the occasion when what we term the F-corona was first seen.[9]

The next important eclipse in India was in January 1898. Numerous expeditions from different countries were scattered along the path of totality from Ratnagiri to Sahdol in former Vindhya Pradesh. Naegamvala had organized a very comprehensive study of both chromosphere and the corona. The report of this expedition indicates the great care and thoroughness that went into the planning of the expedition. The other two important teams were led by Evershed and Lockeyer. All observers obtained flash spectra during this event.[9] [23]

ASTRONOMY DURING THE FIRST HALF OF THE PRESENT CENTURY

Major advances in astronomical research in India were made by Indian scientists in the present century. This was possible due to a fortuitous combination of scientific developments and astronomical events. Naegamvala's observation of the solar eclipse of 1898 broke the psychological barrier of Indians achieving scientific objectives. The appearance of Halley's comet in 1910 created widespread new interest in the subject. The establishment of Kodaikanal and Nainital observatories rekindled the interest in astronomical observations. In addition, the spread of science education in the universities fostered a general awareness of celestial phenomena. Detailed descriptions of development of astronomical activities are described in the following sections.

KODAIKANAL OBSERVATORY

An interesting and unusual factor which contributed partially to the establishment of the Kodaikanal Observatory was the Madras famine. Pogson had thought earlier of an observatory on Palani or Nilgiri Hills, particularly for the photographic and spectroscopic observations of the Sun and stars, but no action ensued in his life time. However, the Madras famine of 1886-87 which occurred due to the failure of the monsoon rains gave a fillip to the establishment of a solar physical observatory. A commission of inquiry which was appointed by the Government to investigate the cause of the famine brought to the notice of government a correlation between the seasonal distribution of rain and sunspot periodicity and recommended that the observatory should investigate this problem. When C. Michie Smith was appointed as Government Astronomer in 1891 the project began to take shape. In 1895, he selected Kodaikanal in the upper Palani Hills as the location for establishing an observatory. The construction work was taken up in 1899 and in the same year the administrative control of this observatory was transferred to India Meteorological Department. This observatory started functioning in 1900. Systematic work in seismology and meteorology was taken up and as soon as the necessary instruments could be erected the study of sunspots, solar photography, prominences and sunspot spectra was commenced.[26] The first solar observations were taken at Kodaikanal in 1901 and spectroscopic astronomy was planned for the observatory. While the two observatories functioned together under the control of a Director at Kodaikanal, work at the astronomical observatory at Madras was confined only to the measurement of time. The new observatory at Kodaikanal had a wide array of spectroscopic equipments specially acquired for solar studies. There were instruments to visually examine the prominences around the solar limb and the spectra of sunspots. Photographic studies included daily white light photography of the solar disc and monochromatic chromospheric pictures with the spectro-heliographs in the light of the lines of ionized calcium and of hydrogen. The uninterrupted series of photographs continues till the present day and forms one of the most unique collections of a record of solar activity available anywhere in the world.[9] Only two other institutions, the observatory at Meudon in Paris and the Mount Wilson Observatory can boast of a comparable collection.[27]

John Evershed, who had been earlier involved in the discovery of ultraviolet spectra of prominences during the total solar eclipse of 1898 in India, joined the observatory in 1905 and later became its Director in 1911. He instituted a programme for photographing the prominences and for systematic investigations of the spectra of sunspots.[28, 29] These observations resulted in two important discoveries in solar physics, viz. (1) the radial motion in sunspots known as the Evershed effect[30, 31, 32, 33] and (2) nature of the sunspot spectra.[34] Evershed found that many Fraunhofer lines in the sunspot spectra were systematically shifted towards the red and he was further able to show that these shifts were due to Doppler effect. His success in observing and measuring the radial motions which had hitherto escaped observations was due in part to the careful methods he had adopted in measuring small shifts in sunspot spectra, and in part to the spectrograph he built with a 6-inch grating given to him by Michelson. He continued his work in this field both at Kodaikanal and also at the temporary field station in Kashmir. For measuring the minute shifts of the spectral lines Evershed devised a positive and negative method of spectrum plate measurement and constructed a special measuring microscope for this purpose. This formed the basis of spectral compensators in use at several observatories. The idea was further developed by R. Leighton fifty years later when he produced the Doppler and Zeeman spectroheliogram by his photographic subtraction technique.[35, 36, 37]

The nature of sunspot spectra was engaging the attention of astronomers at that time. Evershed simultaneously with Fowler, Hale, Mitchel and Adams reached the conclusion that the spectra of sunspots were similar to those of stars of spectral class K.[23] C. Nagaraja Iyer at Kodaikanal obtained reversal of the D3 line of helium in the penumbra of spots.[38] Evershed proved that all spark lines are weakened in the spot; a fact which was later explained by the ionization theory. Several other papers by Evershed published from Kodaikanal call for mention. High dispersion spectrograms secured of Venus showed that the line shift was unaltered when light reflected from the far side of the Sun was examined. In 1918, the spectra were obtained of Nova Aquilae during the first two weeks after the outburst of radiation.[39] Evershed deduced from the initial high outward velocity of gases, compared with the velocities in prominences, that only the gases of the star's original chromosphere would be driven out if the repulsive force was light pressure. He emphasized the presence of sharp non-displaced absorption of H and K lines in the spectrum and identified their source with interstellar gas clouds. A high dispersion spectrogram was secured of Sirius and Evershed pointed out the large widths of the absorption lines especially of hydrogen.[40]

Evershed measured the limb spectra and compared them with the spectrum at the centre of the disk for a study of solar rotation and of the shift toward the red end of lines at the limb. At one time he was inclined to attribute this shift to motion, but later when Einstein gravitational displacement was recognized as a factor to be taken into account, Evershed made further studies of the question.[41] His final view was that the Einstein effect accounted for most of the red-shift at the limb but there remained a definite unexplained residual shift.

Evershed also participated in the observations of the solar eclipse at Wallal, Western Australia. The main purpose of the expedition was to photograph the star field surrounding the Sun on a very large scale and to determine the deflection of light near the Sun by comparison with photographs taken later with a star field at the same altitude. But due to some defects in the instrument the experiment failed.[28, 42]

T. Royd's early papers dealt with periodicities in prominences and their distribution on the solar disk. He compared solar observations to laboratory spectroscopic work and attempted to deduce the variations of density over the solar disk. His most important contribution in this field was the measurement of lines at the extreme limb of the Sun observed at solar eclipse of June 19, 1936. He was a member of the team sent to Japan and the only one to get any results as the sky was clear only for a short while.[23, 43, 44]

A. L. Narayan's early work at Kodaikanal was in the field of atomic spectra and a number of papers were published by him and his co-workers. Among them are the spectra of doubly and trebly ionized lead, the hyperfine structure of indium and thallium, arc spectrum of arsenic, the fine spark spectrum of bromine, the resonance lines of thallium and their probable absence in the Sun.[46] A photoelectric photometer for the direct measurement of the intensities of Fraunhofer lines was constructed by Narayan and the profiles of a few Fraunhofer lines near the centre and the limb of the Sun were studied by him and his co-workers. Among the investigations carried out under the direction of Narayan may be mentioned the studies on band spectrum of phosphorous which led to the conclusion in favour of the existence of the P_2 molecule in the Sun.[26, 45]

NIZAMIAH OBSERVATORY

Nizamiah Observatory which was started in 1908 celebrated its Platinum Jubilee in 1983 and can justifiably be proud of a distinguished history. The observatory came into existence in 1901 when a rich nobleman of Hyderabad, Nawab Zafar Jung acquired a 15-inch Grubb refractor from England and started a private observatory at Begumpet, Hyderabad and sought the permission to call it Nizamiah Observatory after the 6th Nizam of Hyderabad, Nawab Mir Mahboob Ali Khan Bahadur. In 1908 the administration of the observatory was formally taken over by the Government and soon after it was involved in a memorable programme of mapping the sky.[47] In this international programme of carte-du-ciel, 18 observatories with instruments of similar type participated. They were entrusted with photographing different zones of the sky. The Nizamiah Observatory observed —17° to —23°; later it was also alloted the zones between +39° to +36° which was originally given to Potsdam.[48] This was carried out with an 8-inch astrograph built by Cooke and it was conducted under the guidance of three Directors-Chatwood (1908-1914), Pocock (1914-1918) and T. P. Bhaskaran (1918-1944). Twelve catalogues comprising observations of 8,00,000 stars were published. During Chatwood's time the construction of astrograph was taken up and the astrograph was installed by the end of 1909.[47] After this, he initiated the work on astrograph catalogue. This work was continued by Pocock who did much towards the completion of the catalogue covering the zones —17°, —18° and 159 plates in zone —19°, 101 plates in —20°.[49] In addition to the work on astrographic catalogue, he studied Nova Aquilae, sunspots, relation between the elements of planets and satellites.[50] Under the enthusiastic guidance of T. P. Bhaskaran, the next director, the programme for the zone —19° to —23° and +36° to +39° was completed. He was mostly a practical astronomer.[51] The 15-inch Grubb refractor of the observatory was erected under his supervision in 1922. He initiated a programme of observations of variable stars with faint minima with this instrument. During the time of Bhaskaran, the observatory which was under the control of the finance department since its take over by Nizam's Government in 1908, was transferred to the Osmania University.[47] M. K. Bappu who was an astronomer at the observatory had contributed a large number of variable star observations. The availability of a spectroheliscope in the mid-forties and a blink comparator extended the sphere of activity of the institution. Proper motion studies of stars in Hyderabad astrographic zone were commenced. In 1944 when Akbar Ali (1944-1960) succeeded Bhaskaran, a programme of double star measurements formed an important addition to the activity. During Akbar Ali's directorship, double star measurements formed an important programme.[52] It was mainly through his efforts that the order for 48-inch telescope was placed and later acquired. He saw the need for a photographic coverage of larger areas of the southern sky and wanted to introduce the new study of photoelectric photometry and made out a case for a Baker corrector for the 48-inch telescope. Akbar Ali was a man of vision and enthusiasm and encouraged young astronomers. One of his proteges was M. K. V. Bappu. In the words of Bappu, Akbar Ali represented 'the best in Islamic culture'. The study of comets, variable stars, lunar occultations, solar activity, study of proper motion of the clusters were pursued at the observatory.

Astronomy in the Universities

In the first half of the twentieth century, outside the Kodaikanal Observatory, astronomical work was mainly alive in some universities. An account of the activities of Osmania University, Hyderabad has already been given in the previous section. Activities of other university centres are described in this section.

1. *Calcutta University.* In the second decade of the present century, Calcutta University was the prime centre for physics in the country. Prof. C. V. Raman, the Palit Professor of Physics was very keen on astronomy and encouraged his students and colleagues in astronomical work. Major impact produced in astrophysics during this time was by a young theoretical physicist M. N. Saha. Saha's greatest contribution is undoubtedly the postulation of the theory of thermal ionization and its application to stellar atmospheres. The equation that goes by his name was first given in the paper "On ionization in the solar chromosphere" published in the *Philosophical Magazine* of October 1920. Saha considered the state of excitation and ionization in stellar atmospheres to be functions of the temperature and pressure of the atmosphere. This was an important application of Bohr's atomic theory to astrophysics and also provided a theoretical basis for the work done by earlier astronomers like Pickering at Harvard Observatory. Spectral classification provided by the Harvard group represented a temperature classification but they had to wait till Saha provided an explanation in 1920. The theory of thermal ionization introduced a new epoch in astrophysics by providing for the first time, on the basis of simple thermodynamic considerations and elementary concepts of quantum theory, a straightforward interpretation of different stellar spectra in terms of physical conditions prevailing in stellar atmospheres. Struve in his book *Astronomy of the 20th Century* has quoted an interesting anecdote. Saha first submitted the paper embodying his theories to the *Astrophysical Journal* whose editor rejected it. His theory was published finally in the *Philosophical Magazine.* The next editor of *Astrophysical Journal* found Saha's manuscript in a box containing the rejected papers. H. N. Russel, commenting upon Saha's theory said, "The principles of the ionization theory will evidently be of great importance throughout the whole field of astrophysics and Dr. Saha has made an application of the highest interest to the question of the physical meaning of the sequence of stellar spectra."[53] Saha was also one of the first few to suggest the importance of UV observations and the necessity of going out of the atmosphere for understanding the stellar mechanisms better.[54]

Besides having prestigious departments of physics and mathematics, the Calcutta University did not have any organization for astronomical studies. Optical telescopes were available in two small observatories of the Presidency College and the St.

Xavier's College. Important theoretical work made by scientists connected with the university included besides Saha and Raman the names of N. R. Sen and N. K. Chatterjee.[58]

2. *Allahabad University*. An active group of astrophysicists grew around M. N. Saha when he moved to Allahabad from Calcutta in 1925. He started work on laboratory astrophysics and encouraged a strong theoretical group in the subject. Some of his associates like P. L. Bhatnagar, A. C. Banerjee, H. K. Sen, D. S. Kothari and R. C. Majumdar all started their career in astrophysics from this university. P. L. Bhatnagar and H. K. Sen worked with D. H. Menzel on stellar interiors.[59]

Theoretical work on the physics of stellar interiors was undertook by D. S. Kothari and R. C. Majumdar. In a series of papers in early thirties, they calculated the opacity of degenerate matter in the stellar cores and the physics of energy transport phenomena following rigorous quantum mechanical treatments.[55 56 57]

3. *Banaras Hindu University*. While Saha and his students worked in stellar atmospheres and interiors, another group led by V. V. Narlikar started work in cosmology at the Banaras Hindu University. V. V. Narlikar endeavoured for the creation of a group in cosmology. He was able to produce a few students who carried out his line of work. [23 60] His son J. V. Narlikar, as also his first student P. C. Vaidya made impacts in this field later.

Amateur Astronomy in Early 20th Century

The role of amateurs in astronomy has always been significant. While the efforts of Indian amateurs have not been on the same scale as some of those in western countries, special mention must, however, be made of a few individuals, viz. Fathers Johann Grueber and Albert O'orville who were contemporaries of Father Richaud.[61] Since then there have been several efforts of amateurs at observing solar eclipses and events like the transit of Venus. We have already mentioned that Nawab Zafar Jung's interest in astronomy led him to establish the Nizamiah Observatory. At Vizagapatnam. A. V. Narsinga Rao with a 6-inch telescope made observations of the transit of Venus and Mercury and also observed many bright comets. The work of amateurs in the study of variable stars is considerable.[9] The pioneer in the study of variable stars was R. G. Chandra from Jessore who from 1919 until the late forties was a regular contributor to AAVSO (American Association of Variable Star Observer). Chandra's observations were made with a 3-inch refractor owned by him. He was later loaned a splendid 6-inch Clark refractor by the AAVSO to extend his observations to fainter stars. [62 63]

In the field of meteors, M. A. R. Khan of Hyderabad made numerous observations. Khan's observations were regularly sent to the American Meteor Society and for many years he was the outstanding observer. Special mention must be made of the amateur association which sprung up during the period to foster the study of astronomy. Way back in 1910 a few gentlemen in Calcutta decided to form a society which was called the Astronomical Society of India. The idea arose from the interest generated during the appearance of the Halley's comet. It attracted a very large membership and in a few months of its starting it had 117 members. The association was divided into various sections and a person was made the director of each section. The Association held lectures and symposia and brought out the *Journal of the Astronomical Society of India.* Ten volumes of this journal seem to have been published, and well-known scientists like C. V. Raman, M. N. Saha, J. Evershed, T. Royds, R. J. Pocock, A. B. Chatwood, and T. P. Bhaskaran have contributed to this journal. C. V. Raman published as many as 6 papers in this journal. It also had interesting articles on grinding of mirrors and how to make one's own telescopes. The Society possessed a 8½-inch reflecting telescope which was housed in the 'Imperial Secretariat Buildings' and was available for use by the members of the society.[9]

H. P. Waran of Madras is credited to have made the largest aperture paraboloid before 1947. He used a grinding machine fabricated by himself for the purpose. The mirror of 24-inch aperture was the primary of a reflecting telescope that could not be completed due to paucity of funds.[9] Another notable effort in amateur telescope making was by S. K. Dhar and Brothers of Hooghly. They started the manufacture of mirrors for reflecting telescopes as an amateur activity and later formed a professional company.[64]

POST-INDEPENDENCE ASTRONOMY

An important landmark in the history of Indian astronomy in the twentieth century is the setting up of a committee under the chairmanship of Prof. M. N. Saha. The committee was constituted in 1945 to draw up plans for the development of astronomical research and teaching in India at the existing observatories and and universities. The recommendations of this committee gave a tremendous boost to astronomical activity. The main recommendations made by this committee are the following :—

1. The establishment of an astronomical observatory with a telescope of large aperture.

2. The extension of facilities of a coronagraph, solar tower telescope, large aperture Schmidt telescope and a laboratory for solar-terrestrial studies.

3. Establishment of a Naval Observatory and nautical almanac section.

4. The need for post-graduate teaching of astronomy and astrophysics at the universities where establishment of observatories with 15-inch aperture telescope was recommended.[65] Most of the committee's recommendations, specially in so far as Kodaikanal Observatory is concerned, have been implemented in subsequent years.

This was also the period in which astronomical research in the other regions of electromagnetic spectrum started to make a beginning. Some important experiments were Karl Jansky's experiments in radio astronomy and the work of Reber confirming

Jansky's early work, theoretical investigation by H. C. Van de Hulst in 1944 predicting the 21-cm radiation and its confirmation 6 years later, the first rocket with scientific pay-load which went up in 1946, and the launching of first artificial satellite in 1957.[53] Several institutions in India encouraged young scientists to pursue astronomy. Saha had created a fund for building a Radio Telescope in India in 1950; the first Radio Telescope was built in 1952 at Kodaikanal to study the Sun. Many groups of scientists all over India intensified their studies of cosmic rays; the Tata Institute of Fundamental Research (TIFR) group organized balloon-borne experiments reaching high up in the atmosphere. This group in course of time developed instrumentation for x-ray and for infrared studies. In the familiar optical band, observatories at Naini Tal, Rangapur and Kavalur were established with modern equipment. In keeping with the general overall expansion on scientific activities, several groups of theoretical astrophysicists were formed in various universities and institutes. A short description of these developments is given in the next few sections.

Optical Astronomy

Observational work in optical astronomy in India today is mainly being carried out at the Indian Institute of Astrophysics in Bangalore, Centre for Advanced Study in Astronomy at Osmania University, Hyderabad, Uttar Pradesh State Observatory at Naini Tal, and Physical Research Laboratory in Ahmedabad; some limited observational work is also being done in a few universities.

Indian Institute of Astrophysics

The old Madras and Kodaikanal Observatory was converted into an autonomous research institute called the Indian Institute of Astrophysics in 1971.[66] Optical observations at the Indian Institute of Astrophysics are being done from the two observatories; one at Kodaikanal and the other at Kavalur which was started in 1967.

Solar Physics. The observatory at Kodaikanal is concentrating on the studies of the Sun. The old instruments by which considerable scientific progress was achieved have been supplemented by modern equipment. A. K. Das, who was Director of this Observatory (1946-1959) (keeping in line with Saha committee's recommendations) equipped the observatory with several new instruments: (i) The new instrumentation at the solar tower consisting of a large solar telescope combined with a powerful spectrograph of exceptionally high dispersion and resolving power; the solar telescope consists of a coelostat with three telescope object glasses of 37.5 cm and 20 cm apertures; it was constructed by the famous Grubb Parsons of England; (ii) a coronagraph built in Paris by the associates of Lyot; this is of 20 cm aperture; (iii) a monochromatic heliograph with Lyot filter; this filter was also purchased from France but the design and construction of mechanical parts for the heliograph were done in the observatory.[67, 68]

The large solar telescope has now a photoelectric magnetograph which makes fine measurements of magnetic and velocity fields on the sun possible. The tower telescope has been used for high resolution studies of the solar chromosphere, of the Evershed effect in sunspots and the five-minute oscillations observed on the solar surface. It has also been utilized for the study of evolution of active regions and some of the characteristics of chromosphere over such areas. A very significant contribution with its aid has been the idenuification that bright fine mottling in the chromosphere is responsible for the relationship found by Wilson and Bappu between K emission line-widths and absolute magnitudes of stars.[69 70]

Solar Eclipse Studies. During the period 1950-1983, the Indian Institute of Astrophysics participated in the observations of six solar eclipses. An expedition headed by A. K. Das went to Iraq in 1952 and to Ceylon in 1955. Unfortunately both the expeditions were frustrated by bad weather at the time of the eclipse. M. K. V. Bappu led the next three expeditions to Maine, USA in 1963, Miahautlan, Mexico in 1970 and in India in 1980. In 1983 a 5 member team led by K. R. Sivaraman went to Tanjung Kodok in Indonesia.[71 72 73 74]

Solar corona research formed the main aspect of these eclipses. Among the important observations during the expeditions, the high resolution coronal photographs with 6 m focus horizontal camera and a fine coronal spectrogram deserve special mention. During the 1970 eclipse, Bappu, Bhattacharyya and Sivaraman identified on the coronal spectrogram emission lines of Balmer series, the helium D_3 line, and H and K lines of ionized calcium which indicated the presence of relatively cooler regions in the corona.[71] These findings were confirmed from the results obtained by the 1983 eclipse team.[74]

During the eclipse of February 1980 when the path of totality crossed the Indian peninsula, an elaborate observational set up was established. Two camps were set up, one at Hosur about 49 km south of Hubli, and another at Jawalgere 50 km west of Raichur. The camp at Hosur housed the long focus camera for the photography of corona, the polarigraph and the coronal spectrograph. The high dispersion multi-slit coronal spectrograph, the spectrograph for rapid sequence photography of the neutral potassium line close to the solar limb, a Paschen Runge monochromator for limb darkening measurements and a telescope with the 0.5A H-alpha filter were set up at Jawalgere camp. The equipments consisted of modern photo-electric image intensifiers, narrow-band polarizing filters and several pieces of sophisticated electronic equipment. White light photographs of excellent quality showed the presence of coronal transients. The multi-slit spectra helped in mapping the turbulent velocities in the corona.

Studies of the solar system, stars and galaxies

Optical observations of the stars and solar system objects have been conducted from both the observatories at Kodaikanal and Kavalur. Until 1960, the main emphasis was in solar physics. But after Bappu became the Director, emphasis was also placed on stellar physics. Kodaikanal had a 20-inch Grubb reflector originally belonging to Maharaja Takhtasingji Observatory, Poona, and also an eight-inch refractor; these were equipped by Bappu with a photometer and a spectrograph. The 20-inch reflector, popularly known as the 'Bhavnagar Telescope' was originally purchased for the Maharaja Takhtasingji Observatory at Poona where K. D. Naegamvala was the Director. After his passing away, the Observatory was dismantled and in 1912 the instruments were transferred to Kodaikanal Observatory. It was the largest telescope in the country at that time, and served as the principal instrument for stellar observations for a long time. Kodaikanal Observatory was invited by the International Mars Committee to join the world-wide photographic and visual patrol in 1954, Three papers on Mars were published using this telescope.[71 77] Other important studies made with this telescope were spectrographic study of Wolf-Rayet stars and Comet Ikeya-Seki. Among other objects, the binary star gamma Velorum, Nova Delphini and several stars of Scorpio Centaurus association were extensively studied. This telescope was later shifted to Kavalur and is now earmarked for Leh where special observations in connection with establishment of a National Astronomical Centre are being planned.

Kavalur in Tamil Nadu was chosen as the suitable site for stellar observations after an extensive site survey. Regular observations started in 1968 with a small telescope, and the big boost for the programmes came with the acquisition of 102-cm reflector in 1972. Several auxiliary instruments have been subsequently added including a vertical Coude spectrograph and an on line computer system for photometric and spectro-photometric studies. A computer-controlled spectrum scanner was designed and fabricated in the Institute's laboratories. The 40-inch telescope was the first to provide some degree of competitive research capability and in a few years of functioning had some striking achievements to its credit.[78] Within a fortnight of its installation, observations made with it during a rare occultation event showed the presence of an atmosphere on Ganymede, a satellite of Jupiter. Prior to this discovery, Titan, the largest satellite of Saturn was the only satellite in the entire solar system known to have possessed an atmosphere of its own; Ganymede thus became the second satellite with visible evidence of an atmosphere.[79] A new technique using microspectra was developed with 102-cm reflector for the detection of quasi-stellar objects. The spectroscopic observations obtained with the Coude spectrograph showed evidence of active regions similar to those on the solar surface on the bright southern star Canopus. The discovery of ring system around Uranus[80] and the outer ring system of Saturn is among the important achievements made with this telescope.

Besides this telescope, the Institute has produced a few smaller telescopes of its own design and commissioned them for observational use. A 38-cm reflector was made in the Kodaikanal worshop in 1967 and was the first telescope to be used at Kavalur Observatory. A 75-cm reflector was fabricated in the Institute's laboratories and is now installed at Kavalur. The Institute has several other telescopes under fabrication including a 60-cm Schmidt for sky survey work. The task of building a large 234 cm optical telescope has been undertaken by the team of scientists and engineers at the Institute. The need for a large telescope for studying fainter objects was felt even during pre-independence days. Saha recommended one in his Committee report and Das in his booklet *Modernisation of the Astrophysical Observatory* has mentioned that the plans to acquire two large telescopes for Kodaikanal, a 100-inch reflector and a 46/34-inch Schmidt Cassegrain telescope, had already been made but due to financial difficulties, it was not possible to get them. It was only during Bappu's period that the plan was sanctioned and the task of building up a large telescope was undertaken. The 2.34 m telescope has been designed and fabricated indigeneously. The mirror has been ground, polished and figured to a very high degree of precision. The mechanical parts have been designed by Indian engineers under the guidance of the Institute scientists. When installed, this will be the largest optical telescope in Asia.[78]

Studies of stellar atmospheres and their compositions using high dispersion spectrograms, lunar occultations of stars, structure and distribution of globular clusters and planetary nebulae, distribution of young stars in galactic spiral arms, close binaries, study of Novae and variable stars are some of the programmes currently undertaken here. In the area of extragalactic astronomy the structure and spectra of the nuclei of galaxies and the structure of nearby galaxies are carried out. Investigations on comets and asteroids also form part of the activity being pursued.

Centre for Advanced Study in Astronomy, Osmania University

The Nizamiah Observatory (which later became part of the Osmania University) had a 15-inch refractor to start with. This was mainly used for variable star observations and occultation programmes. In addition to this there was an 8-inch astrograph with a 10-inch finder telescope. It also had a spectrohelioscope supplied by Messers Howell and Sherburne, Pasadena and observations with this instrument were seriously taken up in 1945. The Observatory participated in the solar and seismological observation programmes during the International Geophysical observation programmes during the International Geophysical Year (1957-1958) and the observation of the Sun during the International Quiet Sun Year (1964-65). Plans to modernize the observatory were taken up with the financial assistance of the University Grants Commission. A number of other measuring instruments and machinary were also acquired. In 1959 a separate teaching department of astronomy was started at the University. Along with K. D. Abhyankar, V. R. Venugopal moved to Osmania and started the first teaching programmes. A. K. Das served as the Director for a short while on his retirement from Kodaikanal. His term ended abruptly due to his sudden death in 1961. R. V. Karandikar who was chosen to lead the team could not join until June 1963. In the intermediate period, K. D. Abhyankar served as in-charge Director. Karandikar, after joining as Director, completed the installation of the 48-inch telescope. A hillock near two villages Japal and Rangapur about 55 km from Hyderabad was chosen for installing the 48-inch telescope and in 1964 UGC recognized the astronomy department and the observatory facilities at the Nizamiah and Japal-Rangapur as a Centre for Advanced Study in Astronomy (CASA). The 48-inch telescope was commissioned in 1968 December. The new facility is being used for photoelectric and spectroscopic observations of variable stars, mainly the eclipsing and spectroscopic binaries. A photoelectric photometer was built in the observatory workshop and has been used with the 15-inch refractor for photoelectric observations.[47] Abhyankar who was a student of Struve encouraged research of binary stars at the centre. Now Hyderabad is one of the leading centres for investigating binary stars.

The path of totality of solar eclipse of 1980 February 16, crossed over the observatory at Japal-Rangapur. The Nizamiah astrograph was shifted there to conduct a special observation of gravitational deflection of light. Polarization studies of solar corona in red and blue light for determining the electron densities were made using the 4½-inch telescope with polariods, mounted on the 48-inch telescope.

Uttar Pradesh State Observatory (UPSO), Naini Tal

This was one of the observatories that came up in the post-Independence period. In 1947 the Government of Uttar Pradesh decided to set up an astronomical observatory and in 1952 an expert committee was formed with A. N. Singh, as the convenor. The Astronomical Observatory was located at Varanasi and started functioning by 1954. A Cooke, gravity-driven, 25-cm refractor, a set of Rhode and Schwarz quartz clocks and a few other accessories were purchased and formed the original observational equipment. A. N. Singh was entrusted with the task of setting up of the observatory. The observatory commenced visual observations of comets, asteroids and double stars with the help of the 25 cm refractor. After the death of Singh, M. K. V. Bappu, a young astronomer was appointed as the Chief Astronomer. He took active interest in the growth of the observatory during the period 1954-1960. It is due to his initiative and vision that the development plans of the observatory were put on a sound base. The role of Dr. Sampurnanand, the Chief Minister of U.P. in connection with the modernization of this Observatory is very important. One of the first tasks of Bappu was to locate a place to install the proposed telescope. After much site testing the Manora Peak in Naini Tal was found suitable. The observatory was soon shifted to Naini Tal and regular stellar observations commenced. After Bappu left for Kondaikanal in 1960, Sinvhal succeeded him as Director and carried out the development projects. The observatory has a 15 cm reflector and another 38 cm reflector telescope. The observatory also has a 52 cm reflector with folded Cassegrain and Coude foci acquired essentially for solar work. The chief facility at this observatory at present is the one-metre Zeiss reflector named as Sampurnanand telescope which is a duplicate of the instrument available at Kavalur. The observatory has an optical workshop which can polish and grind mirrors upto 75 cm diameter. The observatory has undertaken several observational programmes like determination of orbital elements and basic parameters of eclipsing binary systems through UBV photometry, determination of temperature and radius variations from energy distribution curves of classical Cepheids, analysis of UBV light curves of RR Lyrae stars, determination of light and colour curves of Delta Scuti stars. Study of latetype stars and photometry of galactic clusters are also being done. In solar system studies, photometric medium-band observations of comets Bennet, Kohoutek, West and Bradfield were undertaken. Naini Tal has also undertaken several occultation programmes. It had observed the occultation of SAO 158687 by Uranus in 1977 and identified the ring system around Uranus thus confirming the observations made at IIA. The observatory has prepared a plan for setting up a large telescope of 4 m aperture at a suitable site in the Himalaya lower range near Naini Tal.

In solar physics, observational and theoretical studies of dissociation equilibrium and profiles of diatomic and triatomic molecular lines based on the various sunspot, photospheric and average facula models are in progress. Study of magnetohydrostatic and magnetohydrodynamic models of prominences have been undertaken. The observatory, while still at Varanasi sent an expedition to Ceylon to observe the total solar eclipse of 20 June 1955. The objective was to carryout the polarimetry of solar corona with the help of photographic coronal polarimeter. But the expedition was unsuccessful due to bad weather. The observatory also participated in the observations of the solar eclipse of February 16, 1980 and carried out a programme on coronal photometry, and photography of the 'flash' and coronal spectra.[81]

Udaipur Solar Observatory

For optical studies of the Sun, a special solar observatory has been set up in Udaipur, Rajasthan. It has a 12-ft solar telescope for high spatial and time resolution studies of solar events.

In 1972 an organization called Vedhashala was set up at Ahmedabad with the aim of doing astronomical research. With their assistance, a solar observatory in the midst of a lake in Udaipur was established for high resolution studies of solar features. Later, however, the organization withdrew its support and the observatory was taken over by the Government of India. At present this functions under the administrative control of the Physical Research Laboratory, Ahmedabad and carries out observations of the Sun. The 12 ft Spar telescope is located in a small island in the midst of Fateh Sagar Lake. Owing to the presence of large body of water, seeing conditions are excellent over long periods during the day. The observatory is mainly involved in high spatial and time resolution chromospheric and photospheric studies of flares and other transitory phenomena.[82]

Positional Astronomy Centre, Calcutta

This centre under the administrative control of the India Meteorological Department, which has been entrusted with the publication of the astronomical almanac, has recently acquired a pair of celestron telescopes (36 cm and 26 cm). The telescopes are intended for visual observations of celestial objects for positional astronomical studies.

Physical Research Laboratory

A telescope of 1.2 m aperture mainly intended for studies in the infrared is currently under fabrication and will be installed at Gurushikhar in Mt. Abu; the telescope is expected to become operational in 1985. Though originally intended for dedicated work in IR astronomy, PRL is planning to use it for optical astronomy as well. A high resolution pressure scanned Fabry-Perot spectrometer has been fabricated by scientists of this Laboratory.[83] At present the scientists have been utilizing the telescopes at Naini Tal and Kavalur for their observations. The laboratory has also constructed a Fourier Transform Spectrometer for high resolution spectroscopy of celestial objects. In collaboration with IIA, PRL has been observing with this instrument several peculiar planetary nebulae to map their velocity fields. PRL has also completed a polarimeter to be operated with 1 m telescope at Kavalur. Polarimetric studies of carbon-rich Mira type long period variables to understand the formation and distribution of circumstellar dust is also in their programme.

Tata Institute of Fundamental Research, Bombay

Optical observational programmes in TIFR were started recently. This centre has been utilizing the telescopes at Japal-Rangapur and Kavalur for certain specialized programmes. In collaboration with the Osmania University they are making optical observations of X-ray sources and some suspected Rs CVn systems, and in collaboration with IIA, optical observations of some infrared sources.

Other Institutions

A solar telescope fed by a coelostat has been in operation at Nehru Centre, Bombay for the past few years. No regular scientific programmes have, however, been undertaken. Punjabi University, Patiala has acquired a 60 cm reflecting telescope. The telescope, however, is still to be installed and brought into regular use.[84] Two colleges in Calcutta, St. Xavier's and Presidency and also the Delhi University have a telescope each on their respective campuses. Although extensively used at one time, the instruments are not in regular use now.

An unaccounted number of small telescopes exist in several educational institutions in the country. Some of the instruments are quite old and have been used for serious observations at some epochs of their existence. Several universities have acquired optical telescopes and these are mainly in charge of the university departments of physics or mathematics. These are almost exclusively used for instructional purposes and not used in any observational programme. In some universities where astronomy is offered as a special subject, some basic observational experiments using these telescopes are included in their curriculum.

Radio Astronomy

Radio astronomical research in India is relatively new. In spite of this late start, there have been significant results in this field. First efforts to start radio astronomy in India were made by Saha in the early 1950's. M. K. Das Gupta from the Manchester group who joined the Institute of Radio Physics and Electronics was called upon to take up a major role in this venture. Saha's premature death, however, caused a setback in the scheme. After his death some of his students and admirers decided to set up a Radio Astronomy Institute in the memory of Saha, and raised a sum of Rs. 5,00,000/- from the public for this purpose. But due to lack of determined efforts in following it up, the project did not see the light of the day.[85] Several other institutes have subsequently ventured into this field as described below.

Indian Institute of Astrophysics

At the Kodaikanal observatory, radio astronomy had its beginning in the year 1952 under A. K. Das when continuous recording of solar radio noise flux was commenced using a 100 MHz interferometer with twin Yagi type antennas. This telescope was designed and built locally using the observatory's own facilities.[86] With available instruments, scintillation observations of Cygnus A and Cassiopeia A were made. In the year 1962 a Kodaikanal-Yale project of recordings the radio radiation of Jupiter at a frequency of 22.2 MHz was also started. Later a 3000 MHz radiometer was in regular operation for solar patrol on a tracking 2 metre diameter paraboloid.[87]

In the 70's a collaborative project between Indian Institute of Astrophysics and Raman Research Institute, Bangalore was commenced. A Decameter Wave Radio Telescope was jointly set up by the two Institutes at Gauribidanur, 100 km north of Bangalore, which became operational in 1979. At present it is one of the largest telescopes of this type in the world. It consists of two long antenna arrays, one oriented in E-W and the other in N-S direction, of lengths 1.5 km and 0.8 km respectively. Operating at a wavelength of 10 metres the telescope can resolve objects whose angular separation is about 25 minutes of arc in the sky.[88] One of the aims of the telescope was to survey and catalogue the galactic HII regions which would appear as absorption region against the background non-thermal continuum. It is being used to study radio emission from various types of celestial objects such as the Sun, the planets Jupiter and Saturn as well as extended radio sources in our galaxy and external galaxies. Some of the important studies made using the Decameter Wave Radio Telescope include (1) the detection of continuum radiation from the outer solar corona during quiet periods, and studies of solar absorption and emission bursts, (2) mapping of electron temperature distribution across the ionized hydrogen region, Rosette Nebula, and (3) detection of diffuse radio emission from the Coma cluster of galaxies. As a beginning in stellar radio astronomy in a guest observers programme, VLA has been used by IIA and TIFR scientists to study ejected hydrogen envelopes from extreme hydrogen deficient stars.

Tata Institute of Fundamental Research

Another group of scientists actively engaged in radio astronomy is at the Tata Institute of Fundamental Research. Radio astronomy at this Institute had its beginning during the middle sixties when H. J. Bhabha extended the facilities of TIFR to construct a radio telescope at Ooty. Bhabha pursuaded young radio astronomers wroking abroad to come home and start work in this field. G. Swarup, M. R. Kundu and T. K. Menon returned from various institutions in the US and started this venture. As a first step, it was decided to set up a high resolution interferometer at Kalyan near Bombay for studying the Sun. The radio interferometer was designed for making solar observations at 610 MHz with a resolution of 2.3 arcmin in East-West and 5.2 arcmin in North-South direction. It consisted of 32 parabolic dishes of 1.8 m diameter located over a base-line of about 630 m in East-West and 256 m in North-South directions. The instrument was first used to make a 2-dimensional map of the Quiet Sun at 610 MHz. It was used for the study of the solar corona and solar bursts. However, as a long-term project it was decided to put up a low cost yet a large and powerful telescope of a new design. A search was made for a suitable location for a large steerable radio telescope and Ooty in South India was chosen as the appropriate place. The Ooty telescope was successfully completed and was made operational during 1970. The telescope is a 530 m long and 30 m wide cylindrical paraboloid placed on a mountain slope aligned with the earth's rotation axis and operated at 326.5 MHz. The initial primary programme was the measurement of positions and extent of radio sources by lunar occultation method.[89] The Ooty Radio Telescope is a spectacular success and has put India in the forefront of radio astronomical research in the world. Some of its major contributions are the determination of the positions and structures of thousands of radio sources with arcsecond resolution which helped studies in observational cosmology in a major way. Discovery of a few new pulsars was achieved through pulsar search programme undertaken by the Observatory. Valuable information on the distribution of electron densities in the galaxy has been secured using the interplanetary scintillation technique for radio observations of radio sources. Several attempts have been made to detect stellar flares. Recently several astronomers have used the VLA for the study of supernova remnants and hydrogen line emission.

As a next step in their programme a more refined equipment was taken up. Ooty Synthesis Radio Telescope (OSRT) consisting of Ooty radio telescope and 6 smaller parabolic cylinders of 112 m $\times$ 7.5 m size spread along a baseline of 4 km have already been installed. The OSRT will provide a new tool to study radio sources with high sensitivity and spatial resolution at meter wavelengths. Using OSRT, mapping of some interesting radio galaxies is already in progress.[90]

Physical Research Laboratory

PRL had started with solar radio observations in late sixties and installed a radio spectrograph for studies of solar bursts. Their interest, however, later changed to interplanetary scintillations (IPS). At the present moment they are setting up a three-station array operating at 103 MHz for these studies. The three stations are located at Thaltej (near Ahmedabad), Rajkot, and Surat. Regular IPS observations of radio sources such as 3C 273 and 3C 298 have been made at varying angles from the Sun and the transition from a weak scattering to a strong scattering region in the interplanetary medium has been identified. Angular sizes of these quasars have also been obtained. The laboratory has also plans to operate the array in VLBI-mode for high resolution (3 arcsec) studies of galactic and extragalactic radio sources.[84]

Raman Research Institute, Bangalore

The Raman Research Institute started its programmes in astronomy after V. Radhakrishnan took over as Director, in 1972. The Institute entered into a collaborative project with the IIA on the construction of the large low-frequency array at Gauribidanur. As already mentioned the telescope is now being used to study radio emission from various types of objects such as the Sun, Jupiter, our galaxy and external galaxies. The scientists of this Institute have also started observational programmes with the Ooty Radio Telescope. Among the programmes being carried out or completed using the Ooty telescope are a very sensitive search for deuterium in the interstellar medium, the accurate determination of positions of pulsars, and a major survey of recombination lines in the galactic plane. The last mentioned programme has produced significant result in the understanding of conditions in the more diffuse part of the interstellar medium in our galaxy. The Institute is currently engaged in constructing a millimetre wave telescope of 10.4 m diameter. Very sensitive receivers to operate in the millimetre wavelength range are being built in the Institute's laboratories.[91]

Osmania University

Although the Centre of Advanced Study in Astronomy possessed good optical set up, their facilities for observations in other bands of electromagnetic spectrum were non-existent until a few years ago. For observations during the total solar eclipse of February 16, 1980 the centre entered into a collaborative plan with PRL and S. A. C. Ahmedabad for observing the Sun in cm wavelengths. Such a set up with a 10 ft steerable dish was installed at Japal-Rangapur Observatory in early 1980 by means of which high resolution microwave brightness temperature measurements were made during the eclipse. The equipment has been retained at site where regular observation of solar flux at 10 MHz are now being carried out.[92]

X-RAY ASTRONOMY

Presently, mainly two institutions in India are engaged in research in X-ray astronomy. These are TIFR Bombay and ISRO Satellite Centre, Bangalore. Earlier, PRL also had a programme in this field but this is now transferred to ISSC. X-ray observations have been carried out mainly using rockets, balloons and satellites.

Rocket-borne astronomical observations have been made in the X-ray range of energy 0.1 to 20 keV. Transient X-ray sources such as Cen X-1, X-2 and X-4, binary sources like Sco X-1 and Cir R-1 supernova remnants and the diffuse X-ray background have been extensively studied in these experiments. Energy spectra of sources, temperatures, electron densities and sizes of the emitting regions have been deduced from these observations. Balloon-borne X-ray astronomical observations in the energy range of 20-200 keV have been carried out by the group for study of hard X-ray emission, from a number of X-ray objects like Her X-1 and Cyg X-1.

The first Indian satellites Āryabhaṭa and Bhāskara designed and fabricated by ISRO were to carry out X-ray experiments. Observations of the intensity fluctuations of a transient nature from Cyg X-1 during April 1975 were reported from the data obtained from the two satellites. Unfortunately the satellites did not operate long enough to provide significant results.

X-ray astronomy programme at TIFR started in 1975. They carried out a few balloon-borne experiments where the X-ray emission from Sco X-1 was detected. The group also collaborated with the University of Calgary, Canada and Astrophysics Laboratory, Frascati in two separate joint research programmes where several X-ray objects like Her X-1, Crab Nebula etc. were studied. Simultaneous optical observations during three balloon experiments were provided by ground-based telescopes at Kavalur and Japal-Rangapur Observatories. Presently, the balloon launching facility near Hyderabad is being used for experiments in high energy range. In a guest observers programme they have undertaken a number of interesting observational programme with the NASA satellites SAS-3 HEAO-1 and Einstein Observatory. These studies have led to the discovery of some new X-ray sources and a new pulsar.[84]

Cosmic Ray Research

Cosmic ray research in India began in 1938 with cloud chamber studies at the Palit Laboratory of the Calcutta University and in 1942 at Saha's house in Darjeeling. Ground-based cosmic rays studies by foreign scientific teams date back to 1926 when Arthur Compton of the University of Chicago collaborated with P. L. Bhatnagar and others from the University of Punjab (Lahore). With combined equipment, they camped on a lake in Kashmir at 17,000 ft for a week measuring the intensity of cosmic radiation at various depths (down to 250 feet). The difficult work was terminated by a blizzard in which the equipment was temporarily lost. In 1955 a five-year plan of development was proposed by Saha for research in cosmic rays. Work was to continue at 8000 ft in Darjeeling with two new stations, one at 7,200 ft at Jalapahar and the other at a point on the Darjeeling-Lhasa Road at 16,000 ft. The work, however, could not progress due to inactivity on the part of government and was abandoned after the death of Saha. Some experiments in cosmic ray research were conducted at the Bose Institute, Calcutta under D. M. Bose and Indian Statistical Institute under P. C. Mahalanobis.[85]

At Tata Institute of Fundamental Research, cosmic ray studies were conducted by carrying nuclear emulsion assemblies and electronic instruments to altitudes of 30-40 km in rubber balloons, and in large volume plastic balloons, in 1950's. Studies were also conducted in Mountain altitudes to study large extensive air showers produced by cosmic rays of energy greater than 10^{13} eV and in a deep underground site in Kolar Gold Fields to investigate the variations and intensity distribution of muons and neutrions. These researches opened up new avenues for the study of solar system. The technique of track revelation in grains found in meteorites and later in

Moon samples was developed and refined to the extent that they led to new discoveries.[89]

TIFR experiments are in progress to study the elemental and isotopic composition of cosmic rays at energies of hundreds of MeV and below using plastic detectors. A joint experiment by TIFR and PRL with a plastic detector assembly capable of giving time resolution with a moving film arrangement was selected by NASA in 1977 for inclusion in their space shuttle.

A variety of problems relating to the origin and source of cosmic rays, their acceleration, energetics and propagation in source regions and interstellar space have also been taken up at TIFR. In addition, studies of the role of cosmic rays in the large-scale dynamics of the galaxy, in relation to exotic objects such as supernova remnants and neutron stars and in problems of cosmological nature are being pursued.

At PRL ground-based cosmic ray detector were used to study temporal variation in their intensities. For these, results of great importance were obtained in fields such as periodic intensity variation, modulation of cosmic rays in the heliosphere, properties of the interplanetary medium, solar flare effects and solar wind effects. Also at PRL the novel techniques of track revelations in lunar and meteorite grains have given very valuable information on its pre-history, i.e. the intensity of cosmic tradition over millions of years. PRL also has a programme in cosmic ray astrophysics.

At the Panjab University, work has been carried out on the composition of cosmic rays using nuclear emulsion technique. Investigation in cosmic-ray astrophysics is also being carried out at the University of Calcutta, and some work in cosmic rays is being done in Gauhati University. Nuclear Research Laboratory at Gulmarg, Aligarh Muslim University and APS University at Rewa are engaged in solar modulation studies.[84]

Infrared Astronomy

Infrared astronomy in India is less than a decade old. Observational programmes are usually collaborative ventures between scientists of different research institutes. Groups at PRL and TIFR are carrying out ground-based IR observations in windows in near IR (1-3 micron) using PbS and InSb detector systems since 1978 and 1980 respectively. IR observations are presently being carried out using the 1 m telescope of Kavalur and Naini Tal observatories and 1.2 m telescope at Japal-Rangapur Observatory. Main programmes by the PRL scientists are the photometric measurements of Be stars, bright stars with special characteristics, open clusters, dark clouds and circumstellar envelopes. In another programme, in collaboration with IIA, observations of characteristics of RCrB stars have been obtained to study the variations of IR flux and the distribution and production of circumstellar dust. PRL and TIFR groups, using the 1-m telescope of IIA detected infrared bursts from the globular cluster LillerI.[92]

Balloon borne MARK II infrared telescope fabricated by the joint efforts of TIFR and Vikram Sarabhai Space Centre, Trivandrum was flight tested in late 1980. The instrument weighing 900 kg and containing most sophisticated components was successfully launched from Hyderabad balloon facility. The instrument performed satisfactorily, but unfortunately since the flight termination control failed the entire instrument was lost. However, the data obtained in December 1980 flight contained considerable scientific information. Infrared signals in 70-130 micron band were observed from Jupiter, Saturn and Orion A. A new system incorporating a mirror of 1 m diameter and an improved star tracker has since been built, but not yet tested in flight.[84]

In a collaborative programme with Meudon Observatory, PRL has participated in far-infrared observations aboard an aircraft. The source observed was Large Magellanic Cloud (LMC). In another collaborative programme with the University of Arizona, photometric observations in the infrared were made of SS 433, BL Lac, and the galactic centre, in addition to the few T Tauri stars from the telescopes at Kitt Peak Observatory, USA. PRL scientists have fabricated a high-resolution Fourier transform spectrometer and spectropolarimeter for studies of the near-infrared. IIA, jointly with the Royal Observatory, Edinburgh has taken up infrared studies of RCrB stars by using the special instrumentation on IRAS (Infrared Astronomical Satellite).[92,93]

A 1.2 m telescope dedicated for IR work at Mt. Abu is presently under fabrication jointly by PRL, IIA and SHAR; this and the 2.34 m telescope now nearing completion will be used for infrared experiments in very near future.

Gamma Ray Astronomy

Gamma-ray astronomy in India is still in its infancy. There have been some collaborative programmes between India and the Soviet Union. During the first phase of the programme, the balloon-borne Natalya 1 gamma-ray telescope was successfully launched. A study of the galactic anticentre region in 6-150 MeV energy region was made. Now the second phase of the programme which involves a joint gamma-ray astronomy experiment on a Soviet satellite is underway.

TIFR has been observing very high energy gamma-rays through Cerenkov light flashes in the atmosphere collected by a series of photon detectors arranged at an observing station at Ooty. A special microprocessor-based photon detector system have been built to accurately measure the time of arrival and shape of optical pulses. The Crab is being monitored with 1 m telescope at Kavalur. A joint TIFR-IIA experiment to study gamma-ray bursts and their relation to optical pulses from Crab Pulsar was undertaken in November 1983. Another experiment for detection of celestial gamma-ray sources has been set up at Gulmarg, Kashmir, by the Nuclear Research Laboratory of the BARC. The main interest here is low energy gamma-ray bursts from supernovae and mini-black-hole explosions.

UV Astronomy

Work on UV astronomy requires the facility of space-crafts or balloons. UV astronomy is being carried out by IIA and TIFR through the guest observers programme of International Ultraviolet Explorer satellite. At present, there is no facility in the country to pursue the study of this important spectral region. Development of such a facility should be attempted soon. The main programmes that are being proposed at IUE are the chromospheric and circumstellar properties of hydrogen-deficient stars and cooler binary stars with hot companions for a study of the nature of the companions.[92]

Theoretical Astrophysics

Research in theoretical astrophysics has been extensively carried out by groups both in the national institutions and several universities. At the Indian Institute of Astrophysics, theoretical research in astrophysics covered many areas. It may be broadly divided into (1) physics of the atmosphere of the Sun and stars, (2) physics of the interstellar medium, (3) extra-galactic objects and high-energy astrophysics, and (4) plasma astrophysics. Various topics in solar and stellar atmospheres consist of radiative transfer in spherical media and fine structures in the solar atmospheres. Studies in interstellar medium comprise of interstellar clouds, grains and ionized hydrogen regions. Aspects of stellar evolution including formation of novae, supernovae, planetary nebulae are actively pursued. Studies of extragalactic objects and high energy phenomena include supernovae and black holes along with stellar content of galaxies, active galactic nuclei, quasi-stellar objects and pulsars. Topics in plasma astrophysics cover MHD processes on the Sun and supernova remnants and radio bursts from the sun.

There is also a large group in TIFR working in theoretical astrophysics. The activities started in 1966 and spread over a number of topics in theoretical astrophysics including atmospheres of cool stars, convection zones in stars, models of pulsars and the state of matter at high density. With the discovery of pulsars, theoretical models were built for explaining the extreme regularity of pulsar periods and to explain the emission mechanism. The equation of state of cold matter has been studied by a number of workers to construct neutron star models. The evolution processes leading to the formation of collapsed objects were studied; the physical properties of white dwarfs, neutron stars and black holes were examined with special reference to their role in the context of pulsars and cosmic X-ray sources. Work is also being done in areas like molecules in comets, planetary physics, models of reflection nebulae in UV, and vertical flow in solar and stellar atmospheres. Different aspects of cosmology including nonstandard models, neutrinos in the universe, and gravitational lensing are being studied.

At the Raman Research Institute, active research has been pursued on various aspects of pulsars. Models have also been proposed for recently discovered milli-second pulsars. Supernova explosions, their mechanism, frequency and consequent relation to pulsar birthrates have been topics of investigations.[91] Studies of interstellar molecular clouds is picking momentum.

The theoretical group of the Osmania University is carrying out research in topics such as dynamics of galaxies, radiative transfer in stellar and planetary atmospheres and positional astronomy. In Naini Tal, theoretical studies concerning the formation of molecular lines in Sun is actively pursued.

At the PRL investigations are being carried on in plasma astrophysics in topics relating to the structure and stability of accretion disks around compact objects and the dynamics of disk galaxies. Emission mechanisms and radiative transfer problems particularly with respect to high energy sources are being carried out.[93]

Research in observational and theoretical astrophysics has also been in progress in several universities. A short list of these centres is given in Table 1.

At Roorkee theoretical studies of the problems of stellar pulsations are pursued. At the Gauhati University areas like nuclear reactions in astrophysics, fission processes in astrophysics, nucleosynthesis and abundance distribution of elements, X-ray bursts, neutron star phenomena, plasma astrophysics have been studied. At Ravi Shankar University principal efforts are on cosmological interpretation of high redshift objects and theoretical investigation of the chemical abundance in extra-galactic objects with particular references to QSOs, active nuclei of galactic and physical processes in extragalactic objects. At Burdwan University topics like properties of QSOs, compact objects and the formation of black holes are being studied. A brief mention of other topics of interest are shown in the Table. 1. Besides these groups, there are a large number of individual scientists in other universities who carry out investigations in various topics of theoretical astrophysics, often single handed. Efforts to extend help to these scientists by way of consultations, participation in symposia and in publications form a major part of activities of the Astronomical Society of India.

ASTRONOMY IN INDIA IN THE 20TH CENTURY

Table 1

List of Universities and Institutions with their Major Areas of Research

1. Aligarh Muslim University	Solar Physics, Cosmic Ray studies
2. Amaravati College of Engineering	Solar Physics
3. APS University, REWA	Solar Physics, Cosmic Ray studies
4. Banaras Hindu University	Solar System Research
5. Burdwan University	General relativity, Gravitation, Cosmology, Astrophysics
6. Calcutta University	Plasma Astrophysics, Cosmic Rays Research, Theoretical Astrophysics

7. Delhi University	Solar System Research, Plasma Astrophysics, Cosmology
8. Gauhati University	Theoretical Astrophysics, Cosmology, General Relativity
9. Gorakhpur University	Astrophysics and Cosmology
10. Gujarat University	Cosmic ray Research, UV, X-ray and gamma ray astronomy
11. Indian Association for the Cultivation of Science	Theoretical Astrophysics
12. Indian Institute of Astrophysics, Bangalore	Solar Physics, Stellar Physics, Interstellar medium, Extragalactic Astronomy, High Energy Astrophysics, Solar Terrestrial Relations
13. Indian Institute of Science, Bangalore	Cosmic Ray Studies
14. Indian Institute of Technology, Kanpur	Solar Physics
15. Indian Institute of Technology, Kharagpur	Solar Physics, Theoretical Astrophysics
16. Jodhpur University	Astrophysics and Cosmology
17. Kumaun University	Astrophysics and Cosmology
18. Meerut College	Solar Physics
19. Nagpur University	Astrophysics and Cosmology
20. Nehru Planetarium	Solar System Studies
21. National Physical Laboratory	Solar System Studies
22. North Bengal University	Cosmic Ray Research
23. Nuclear Research Laboratory	Solar Physics, Cosmic Rays
24. Osmania University	Solar Physics, Theoretical Astrophysics, Binary star research
25. Panjab University	Theoretical Astrophysics, Cosmic Ray Studies
26. Physical Research Laboratory, Ahmedabad	Solar System Research, Radio Astronomy, Infrared Astronomy Optical Astronomy, Cosmic Ray Studies, Plasma Astrophysics
27. Poona University	Theoretical Astrophysics
28. Punjabi University	Stellar Physics
29. Raman Research Institute	Theoretical Astrophysics, Radio Astronomy, Millimeter Wave Astronomy
30. Ravi Shankar University	High Energy Astrophysics
31. Roorkee University	Theoretical Astrophysics
32. Tata Institute of Fundamental Research	Solar System Research, Radio Astronomy, Infrared Astronomy, Cosmic Ray Studies, Theoretical Astrophysics
33. Udaipur Solar Observatory	Solar Physics
34. Uttar Pradesh State Observatory	Solar Physics, Optical Astronomy, Theoretical Astrophysics

As mentioned in an earlier section, N. R. Sen in Calcutta University and V. V. Narlikar in Banaras Hindu University may be considered as pioneers of research in general ralativity in India. In the Calcutta region some interesting work came from individual research workers, e.g. B. Datta's 'solution of gravitational collapse' which was published in 1938 (one year before the oft. quoted paper of Oppenheimer and Snyder), and S. D. Majumdar's work on 'Einstein-Maxwell equations' in 1947, which came to be known as Majumdar-Papapetrov type solutions. A. K. Ray Chaudhuri's contribution to rotating shearing cosmological models in the early 1950's became well-known as Raychaudhuri's equation. The BHU school trained several research workers in general relativity, some of whom continue to be active in places like Ahmedabad, Gorakhpur and Kolhapur. The first student of V. V. Narlikar was P. C. Vaidya whose solutions of a radiating mass are often quoted today. Students of Narlikar have carried today the tradition of general relativity research at BHU.

Presently, much of the research in relativity and cosmology comes from universities like BHU, Gorakhpur, Calcutta, Burdwan, Gujarat, Gauhati, Bangalore, Mysore, Pune, Bhavnagar, Kolhapur, Kumaon etc. Amongst research Institutes mention may be made of S. N. Bose Institute at Calcutta, Matscience at Madras, Raman Research Institute, Indian Institute of Science, Indian Institute of Astrophysics all at Bangalore, PRL at Ahmedabad and TIFR, Bombay. The work in relativity in India is in the areas of exact solutions, Petrov classification of various space-times, astrophysics of highly collapsed objects, accretion discs around black holes, gravitational lens and screens, problems in unified field theory, Brans-Dicke theory and the Einstein Maxwell theory, anisotropic cosmologies and quantum cosmology. The Indian Association for General Relativity and Gravitation was formed in 1969. It has a membership of nearly 175 persons.

Amateur Astronomy after 1950

There has been an increase in the number of active amateur astronomy groups in the third quarter of the 20th century. The most active groups are in Bombay, Calcutta, Bangalore, Madras, Baroda and Goa.[94] Since there is no published information available about general amateur activity in India, it is difficult to prepare a comprehensive report.

Bombay Amateur Astronomers' Association was started in 1976 with R. V. Kamath as the president of the association. The association has built up a member strength of 300. Their main activity includes lecture courses; they regularly bring out a newsletter called M51, encourage members to take up telescope making and observational programmes. Observations of eclipses, lunar occultations, astrophotography, history of astronomy and sky watching programmes are some of the activities followed by them. The association has a Cassegrainian Schmidt telescope 'Celestron 8' and other smaller telescopes. They took part in the total solar eclipses of 1980 in India and 1983 in Indonesia and results of these observations were published in the International Union of Amateur Astronomers.

Bangalore and Bombay groups participated actively in 1980 total solar eclipse which was visible in India. The Bombay group obtained a good colour picture of solar corona using Kodachrome film and a Celestron telescope. The Bangalore amateur group tried to make polarization measurements along with the white light photographs of solar corona. The Bombay amateur group attempted to measure the speed of shadow bands along with the white light photography during the total solar eclipse in Indonesia in May 1983. The Association of Bangalore Amateur Astronomers was established on February 15, 1976. The Association was formally inaugurated on July 4, 1976 by M. K. V. Bappu. They hold meetings every month usually accompanied by a review lecture by some active astronomers. They have conducted courses on basic astronomy and amateur telescope making. They constructed an F/7 Newtonian telescope of 9-inch aperture in 1981 by utilizing purely voluntary contribution in cash and kind.

In Madras the two well known associations are the Madras Astronomical Association and the Yuri Gagarin Club. The Amateur Astronomical Association in Calcutta is in St. Xavier's College. Another active society in Calcutta is the Sky Watching Society, which organizes sky watching camps. It has a 3-inch refracting telescope and 10-inch reflecting telescope.

Amateur astronomy is also encouraged in several universities. Some of the educational institutions equipped with small telescopes are the Presidency College of Madras and Calcutta; Elphinstone College, Bombay; St. Xavier's College, Calcutta and Bombay and St. Joseph's College at Bangalore. Many other educational institutions in the country have sponsored astronomical observations as a part of their routine education programme.

Association for Promotion of Astronomy in India

In 1952, when the Indian Science Congress was held at Calcutta and the University of Calcutta was the host, the new Indian Astronomical Society was formed. This idea was earlier mooted by Saha but unfortunately due to his untimely death in 1956 it could not be carried out. Some important members of the society were A. C. Banerjee, N. R. Sen, S. Basu and M. K. V. Bappu. The principal objectives of the society were to promote and encourage the study of astronomy, astrophysics, astronautics and allied subjects and to bring out a society journal which will carry original results in this field. The society aims to encourage lectures and symposia, undertake popularization of the subject and to improve the facilities for observations. However, due to many reasons the association could not carry out its objectives. It was in 1974 that some of the activities were started again, under the efforts of A. K. Saha and N. C. Lahiri. In 1980, it succeeded in bringing out the first issue of the society publication 'Akash'.[95]

Since the Calcutta Association was not very active, the astronomical community in India was feeling the need for an association for promotion of astronomy and related branches of science in India. Hence the Astronomical Society of India was formed in 1972 with its headquarters at Osmania University, Hyderabad. To fulfil its objectives it has undertaken various functions like encouragement of the study in all aspects of astronomy and astrophysics, to bring out a journal, to hold scientific meetings for presentation of original research papers and review talks at least once in two years. The society has been very active and has largely succeeded in achieving the objectives. They have undertaken programmes to popularize the science of astronomy among the educational institutions and general public in India through lectures and scholarships and helped inclusion of courses in astronomy in school and university curricula to a limited extent. It has assumed an important task of encouraging amateur astronomy in India. The Bulletin of the association is being published regularly and is considered as one of the leading journals in astronomy in the country.[96]

PUBLICATION

The Kodaikanal Observatory Bulletin (KOB) has long been the medium of publication of research results at Kodaikanal. The first Bulletin was published in the year 1908. These bulletins, in addition to research contributions, contain the date of the solar geomagnetic and ionospheric observations carried out at Kodaikanal.[69] In 1966, the Radio Science Division of the PRL, New Delhi, took over the responsibility of publication of solar and geophysical data. After the formation of the Indian Institute of Geomagnetism in 1971, the new body took over the responsibility of publication of geomagnetic data as a national endeavour. Accordingly the publication of solar geomagnetic and ionospheric data from Kodaikanal was discontinued from 1978 and the bulletins now contain only research papers. In addition to the KOB there was a supplementary publication titled Memoirs of KOB of which only one volume has so far been published. Nizamiah Observatory has been bringing out the contributions of the Nizamiah Observatory since 1962 at periodic intervals. They contain research papers published by the observatory staff.

An important International journal titled *Journal of Astrophysics and Astronomy* has been started by the Indian Academy of Sciences, Bangalore. The publication carries papers of a high standard. The publication signifies a bold venture of the Academy who felt that the expanded astronomical activities in the country deserve a journal of international stature.[97] The journal has a Board of editors drawn from eminent astronomers all over the world. M. K. V. Bappu as its first chairman ably guided the first few years of the journal and set it on its way towards a great future.

As mentioned in earlier section, Astronomical Society of India also regularly publishes a journal titled *Bulletin of Astronomical Society of India* and also the *Memoirs of the Astronomical Society of India*. Two issues of the *Memoirs* have been brought out till now. Four issues of the *Bulletin* are published in a year. The memoirs are special issues brought when new important results containing large amounts of data are to be published.

The Indian Astronomical Society has also been active recently having brought out two issues of their journal 'Akash'.

HIGHLIGHTS OF ACCOMPLISHMENTS IN ASTRONOMICAL RESEARCH IN TWENTIETH CENTURY INDIA

We may conclude this chapter by reviewing briefly the highlights of astronomical research in India during the 20th century. This was a period when the phase of astronomical research changed dramatically and rapidly. On the observational front the period saw the coming in of large telescopes, and more sensitive detectors, which enabled the scientists to reach much further in the universe, thereby expanding the old boundaries. New observational windows in the radio and later in other bands of electromagnetic spectra opened up, bringing a great deal of new information which revolutionized our ideas about the universe. On the theoretical side, Einstein's General Theory of Relativity created a new concept of space and time; the newly acquired capabilities of measurements of starlight with laboratory precision encouraged several schools of theoreticians to realistically model reaction processes in astrophysics. The major glory of advancements in the subject was cornered by nations with developed scientific groups whereas efforts by individual scientists generally took a back seat. India was a dependent colony for more than half of this period, where encouragement to fundamental research had a low priority in the development plans of the state. In spite of all these drawbacks several noteworthy achievements by Indian scientists were made in astronomical research. While some of them were forced to migrate from the country in search of suitable facilities, quite a few had sought to develop the facilities from within. This development perhaps marks the pinnacle of achievements of this period. Most of this work was done in the post-independence period by several groups of young scientists, and resulted in the creation of a chain of observatories. The names of M. K. V. Bappu, G. Swarup and V. Radhakrishnan stand out among this group. If we have to single out the most important achievement in theoretical astrophysics by an Indian scientist it should perhaps be M. N. Saha's Theory of Thermal Ionization. Saha almost single handedly worked out his famous "Ionization Formula". This work has been justly described by Eddington as one of the ten most outstanding discoveries in astronomy and astrophysics since the discovery of the telescope.

D. S. Kothari and his colleagues investigated the properties of degenerate matter and in a series of important papers discussed topics such as opacity coefficient, transport phenomena and ionization of degenerate matter. S. Chandrasekhar also made important contributions to the same field before migrating abroad. The work on cosmology and relativistic astrophysics pioneered by N. R. Sen in Calcutta and V. V. Narlikar in Banaras yielded several new ideas worth noting. In subsequent years, A. K. Raychoudhuri's "Raychoudhuri Equation" describing rotating, shearing cosmological models and P. C. Vaidya's "Vaidya Metric" for a radiating spherical star stand out as highlights. More recently J. V. Narlikar has made outstanding contributions to the theory of C-field and steady-state cosmology and developed Hoyle-Narlikar Theory of Conformal Gravity in collaboration with Hoyle. In observational astronomy, notable work on the Sun was done by Evershed and Royds at Kodaikanal and on the "Carte due Ciel" programme at Nizamiah Observatory. Later developments were the modernization of solar observational equipment at Kodaikanal by Das and Bappu, establishment of Naini Tal and Kavalur Observatories by Bappu, and installation of medium size optical telescopes at Rangapur, Naini Tal and Kavalur, with modern observational accessories. A major venture undertaken which is close to completion is the indigenous fabrication of a large optical telescope of 234 cm aperture at Kavalur.

For observations in the radio wavelengths the large cylindrical paraboloid at Ooty is a major construction. The array has also been extended by the addition of more telescopes in interferometric arrangements. The OSRT (Ooty Synthesis Radio Telescope) is one of the most powerful instruments of its type in the world today.

At still longer wavelengths, the Gauribidanur Low Frequency Array possesses one of the largest collecting area available today. This is a unique instrument enabling scientists to probe the universe in the decametre wavelengths.

In the field of X-ray astronomy and cosmic rays, several balloon, rocket and satellite borne payloads have been designed, constructed and launched. This definitely constitutes a big step forward in our scientific efforts.

Similar efforts are under way in the fields of infrared and millimetre wave astronomy. Considerable progress in instrumentation has been achieved.

Several important results in astrophysics have been found by employing these newly developed observational systems. In the field of solar physics, detailed studies of photospheric oscillations have yielded important data on solar seismicity, dynamics of the regions surrounding sunspots and near the temperature minimum have been studied in detail and a long-standing problem of width-luminosity relation of Wilson and Bappu has been solved. Observations during the three total solar eclipses have confirmed the existence of cooler regions in the lower corona. Studies of rapid features in solar decametric bursts have thrown considerable light on the mechanism of these phenomena.

In studies of solar system astrophysics, several epoch-making discoveries have come out of a series of planetary occultations. Discoveries of the rings of Uranus and the outer rings of Saturn were made from observations done with the telescopes at Kavalur and Naini Tal. Interplanetary scintillation studies, and the observations of progressive change in cometary spectra with varying heliocentric distances have given a much clearer picture of the interplanetary medium.

In extragalactic studies, impressive results are obtained by S. M. Alladin and his colleagues in modelling theoretically the dynamical interactions between galaxies. Observational and interpretative work of good standard on peculiar and radio galaxies and quasars is being carried out at the Radio Astronomy Centre of TIFR and at Indian Institute of Astrophysics. While studies in stellar physics, interstellar matter and galactic structure are avidly pursued in all the optical observatories and by groups in TIFR and PRL, the radio observations are continuing at Ootacamund and Gauribidanur. A strong group on the studies of pulsars and supernova remnants, as also on interstellar molecular clouds, is emerging at the Raman Research Institute.

Narration of achievements by Indian scientists will be incomplete, if note is not taken of the outstanding work done by several scientists, who either migrated abroad or did a significant portion of their work while abroad. Top of the list is, of course, occupied by the Nobel Prize winning Indian born scientist, S. Chandrasekhar. A major part of the original discoveries of M. K. V. Bappu in stellar spectroscopy was achieved while still in USA. So was the monumental work of M. R. Kundu and K. Nandy whose outstanding contributions were made while working abroad. There were several others, notably H. K. Sen, T. K. Menon, S. S. Kumar, V. Radhakrishnan who have left indelible marks in the international astronomical literature by their significant achievements.

When the decision was taken by IAU to name newly discovered lunar craters on the far side of the Moon after the departed scientists, names of seven eminent scientists from India were selected. The names are: J. C. Bose, P. C. Ray, H. J. Bhabha, M. N. Saha, S. K. Mitra, A. K. Das, and J. B. S. Haldane. In a later meeting three more names were added and those were C. V. Raman, V. A. Sarabhai and S. N. Bose. Besides these, the Moon's surface also bears the names of three British astronomers who spent the best years of their lives in the persuit of science in India. The names are those of N. R. Pogson, J. Evershed and T. Royds. These are token salutations of the International Community of astronomers to the great minds who have enriched Indian science in the present century.*

*We are indebted to many indixiduals for thei. collection of basic information. We are specially thankful to Prof. Ch. V. Sastry, Dr. T. P. Prabhu and Dr. P. K. Das for their help in the preparation of parti of the manuscript, to Dr. N. Kameswara Rao for carefnlly scrutinizing the manuscript and making several useful suggestions, and to A. M. Batcha, N. Valsalan, K.T. Rajan, S. Pramila and K. Padmavathi for typing work at various stages.

APPENDIX

A Chronology of Astronomical Event in india in The Twentieth Century

1901 Establishment of Nizamiah Observatory
Solar Observations started at Kodaikanal

1904 Spectroheliogram sequence started at Kodaikanal

1908 Nizamiah Observatory taken over by Nizam's Government

1909 Evershed effect discovered

1910 Apparition of Comet Halley
Astronomical Society of India established

1912 Nizamiah Observatory joins Carte du Ciel programme

1913 Evershed carried out solar experiments in Srinagar, Kashmir

1920 M. N. Saha's paper on ionization in solar chromosphere

1921 Saha's paper on stellar spectra

1932 D. S. Kothari's paper on degeneracy in stellar core

1936 Royd's measurement of solar limb spectra

1937 Saha describes the idea of stratospheric solar observatory

1945 Saha Committee on Astronomy
Tata Institute of Fundamental Research established
Spectroscopic observations at Nizamiah Observatory

1951 UP State Government decides on an astronomical observatory

1952 Radio observations of the Sun started at Kodaikanal
Indian eclipse expedition to Iraq

1953 Physical Research Laboratory established

1954 Astronomical Observatory at Varanasi started
Kodaikanal joins International Mars Programme

1955 Naini Tal Observatory started observations
Indian eclipse expedition to Ceylon

1957 Indian Astronomical Ephemeris released
Intensified solar observations undertaken in connection with IGY

1963 First rocket flight from Thumba
Solar Eclipse Observations in Maine, USA

1964 Centre of Advanced Study in Astronomy was opened at Osmania University
India admitted as a regular member of IAU

1965 Solar magnetograph observations started at Kodaikanal
TIFR takes up Radio Astronomy Programme

1967 Kavalur Observatory established

1968 Rocket flight with X-ray payload from Thumba

1970 Indian Eclipse Expedition to Mexico results in new coronal data
Ooty Radio Telescope commissioned
Names of seven Indian scientists put on Moon

1971 Formation of Indian Institute of Astrophysics
First photoelectric observation of planetary occultation from India
International Mars programme observations at Kavalur

1972 Two one-metre telescopes installed at Naini Tal and Kavalur
Ganymede atmosphere detected
Raman Research Institute starts Astrophysical research
Astronomical Society of India constituted

1974 IIA starts on 234 cm telescope project
Vedhashala undertakes observational programmes
Aryabhata with X-ray Payboard launched.

1975 Computer controlled spectrum scanner commissioned at Kavalur

1976 Three more Indian names put on moon

1977 Discovery of Rings of Uranus

1978 PRL starts 122 cm IR Telescope project

1979 M. K. V. Bappu elected as President IAU
First detection of IR bursters at Kavalur

1980 Total Solar Eclipse in India
Balloon-borne far IR telescope launched

1983 Indian Eclipse Expedition to Indonesia

1984 Discovery of Outer rings of Saturn