RAA 2019 Vol. **19** No. **10**, 138(16pp) doi: 10.1088/1674–4527/19/10/138

http://www.raa-journal.org *http://iopscience.iop.org/raa*

Research in Astronomy and Astrophysics

SCIENTIFIC REMINISCENCES

Journey through the birth, growth and maturity of X-ray astronomy

Prahlad Chandra Agrawal

MU-DAE Centre of Excellence in Basic Sciences, Mumbai University Campus at Vidhyanagari, Kalina, Santacruz (east), Mumbai-400098, India; *prahlad.agrawal@gmail.com*

Received 2019 July 23; accepted 2019 August 13

Abstract In this biographical account, I recall my scientific journey that began in 1961 when I joined as a Physics Trainee in the BARC Training School and after one year course was admitted in TIFR as a Research Associate. During 1962–1967, I worked on determination of the He^3/He^4 ratio in cosmic rays using a gas Cerenkov counter and also used a scintillation + solid Cerenkov detector to measure flux of protons and helium nuclei in primary cosmic rays. I also developed a large area scintillation-Cerenkov detector with a spark chamber between them for measuring charge composition of primary cosmic rays. I joined the X-ray astronomy programme in 1967 initiated by Prof. B. V. Sreekantan and played a leading role in developing a balloon borne hard X-ray instrument for studying time variability and energy spectra of cosmic X-ray sources. We carried out a series of balloon experiments and studied temporal intensity variation and energy spectra of X-ray objects like Sco X-1, Cyg X-1, etc. Results on rapid intensity changes and spectra appeared in a series of publications based on which I obtained a Ph.D. degree in 1972. Immediately afterwards, I joined Prof. Gordon Garmire at Caltech as a Research Fellow (a post-doctoral position) to work with him on the low energy component of HEAO A-2 experiment. The instrument was developed and successfully realised. Working on this satellite experiment was a thrilling experience which exposed me to the technical complexities of space instruments. The HEAO-1 satellite was launched in 1978. During 1978–1979, Guenter Riegler and I, working at JPL, reported detection of intense soft X-rays from several classes of extragalactic and Galactic objects like new BL Lacs, a new AM Her binary, coronal X-rays from active stars, etc. After returning to TIFR, I developed a rocket experiment with K. P. Singh to map the spatial and spectral distribution of the Soft Diffuse X-ray Background. At the same time, I also designed 15 cm deep Xenon filled Proportional Counters (XPCs) of $\sim 2500\,\mathrm{cm}^2$ area for balloon experiments which were done during 1983–1990 and produced new results on several X-ray binaries. During this period I also developed a proportional counter (PC) based satellite instrument and submitted a proposal jointly with the astronomy group at the Indian Space Research Organization (ISRO) for an Indian X-ray Astronomy Experiment (IXAE). After success of the Polar Satellite Launch Vehicle (PSLV), the IXAE instrument was included on the top deck of the IRS-P3 satellite that was launched in March 1996. Despite the severe limitation of a polar orbit, the IXAE observed a good number of X-ray binaries and produced interesting results, with the most notable being quasi-regular bursts from a new transient, GRS 1915+105, which turned out to be an enigmatic black hole source. Following success of the IXAE, a proposal for an ambitious multiwavelength astronomy satellite, named ASTROSAT, with broad spectral coverage in the optical, NUV, FUV, soft X-ray and hard X-ray by a suite of instruments, was submitted to ISRO and finally approved by the Govt. of India in 2004. Over the next 10 years, the development and fabrication of the five ASTROSAT instruments were accomplished and a PSLV launch on Sept. 28, 2015 placed ASTROSAT in a 650 km circular orbit with 6 degree inclination. The ASTROSAT instruments have been performing well for ~ 4 years and have observed more than 500 cosmic sources. Results from ASTROSAT have appeared in a large number of journal publications. Successful realization and performance of ASTROSAT marks culmination of my research career. I formally retired as a Senior Professor from TIFR on 2006 April 30 on attaining the age of superannuation. However by agreement with TIFR, ISRO designated me 'ISRO Chair Professor', which was later renamed as ISRO Satish Dhawan Professor, and asked me to continue to lead ASTROSAT as PI. At the end of my tenure as ISRO Professor on 2011 April 30, I relinquished the PI position. I am at present affiliated with the MU-DAE Centre of Excellence for Basic Sciences, Mumbai University Campus at Mumbai as an Emeritus Professor.

Key words: TIFR — X-ray Astronomy by balloons — rockets and satellites — Indian Astronomy Satellite ASTROSAT

1 EDUCATION AND SELECTION IN TATA INSTITUTE OF FUNDAMENTAL RESEARCH (TIFR)

I was born in 1941, in a small town known as Ratlam, located in the present Indian state of Madhya Pradesh (which literally means Central Province). All my education, from primary to secondary and right up to graduation, happened there. In May 1961, I completed my Bachelor of Science (B.Sc.) degree from the Government College in Ratlam with physics, chemistry and mathematics as my subjects. I secured a first class with a good rank in the university, thanks to my own hard work and the help of excellent teachers.

I was fascinated with recent developments in physics and wished to pursue a post-graduate degree, but the Master's programmes in this subject were not taught in Ratlam. I would have to enroll in the well-reputed Holkar College in Indore, which offered post-graduate courses in different science streams. Coming from a large family of modest means, this was a challenge. My father was in a difficult financial position at the time and was unable to support my higher studies. Fortunately, I was successful in obtaining scholarships from two private trusts.

Hoping that with the scholarship amount, I would be able to meet my educational expenses, I got admitted in the M.Sc. (Physics) course of Holkar College. I had barely spent a month there, when I realised that the scholarship was enough to meet my living expenses but there was no money to buy books or pay the college fee. It seemed like I would have to leave the course and return home. This thought was extremely depressing.

Just around this time, one afternoon, my elder cousin came to my room and gave me a wonderful piece of news. There was a telegram from the Department of Atomic Energy (DAE) informing that I had been selected as a Trainee for the physics course in the Atomic Energy Establishment, Trombay (AEET) Training School (now known as Bhabha Atomic Research Centre (BARC) Training School). I would have to report in Mumbai at the Training School in the next 4 days! I was overjoyed at this God-sent opportunity and lost no time in reaching Mumbai; addand there I was, reporting to the Hostel at the BARC Training School at Bandra in mid-July 1961.

The truth is, I had completely forgotten about this! Two months ago, there had been an advertisement in the newspaper calling for B.Sc. or M.Sc. students with outstanding grades to apply as Physics Trainees. Well, I had sent my application and was among the thousand odd candidates called by DAE for an an interview in Mumbai. Only 50 would finally be selected. At the interview I was questioned extensively on various topics in physics and asked to solve a few B.Sc. level mathematics problems. I thought that I answered most questions well. At the end of the interview I was asked to go for medical tests. Subsequently, I returned home and since I had not received any communication from DAE whatsoever, I had just assumed that I was not successful.

So it was with great anticipation and eagerness that I joined the BARC Training school. The one year course was quite dense, grueling and comprehensive, covering almost all major theoretical and experimental areas of physics. Besides the usual courses it included Reactor Physics, Interaction of Radiation with Matter and Radiation Detectors, Analogue and Digital Electronics, etc. As soon as a part of the course was completed, there was an examination in that subject. On virtually every Saturday there was an examination, so in a year I must have appeared in about 35 tests covering the various topics! It was a demanding and mentally challenging time.

On completion of the course, there was a comprehensive interview for placement of the successful trainees in the various divisions of BARC and Tata Institute of Fundamental Research (TIFR). Usually, the top ten physics students were offered a position in TIFR for engaging in basic research. I was selected to work in the High Altitude Studies (HAS) Group at TIFR which was engaged in studies of cosmic rays using electronic radiation detectors flown by plastic balloons and carried to altitudes of 30 to 40 kms.

2 EARLY YEARS IN TIFR, ITS AMBIENCE AND COSMIC RAY RESEARCH

When I joined TIFR in July 1962, it had moved into its new premises overlooking the Arabian Sea, in Navy Nagar, at the south end of Mumbai. The magnificent building of TIFR and its ambience fills one with awe and admiration for Dr. Homi Bhabha, who conceived its layout and design and oversaw its construction.

The academic atmosphere at TIFR was very lively. Researchers had freedom of working hours with the institute remaining open 24 hours a day, all days of the week. There were weekly seminars organised by different groups in their research areas. The most important forum for discussion was the weekly Physics Colloquium on Wednesdays which was a regular feature of the academic calendar of TIFR. It was a forum for presentation of ongoing research in TIFR, as well as discussion of new discoveries and developments by distinguished Indian and foreign scientists visiting TIFR.

Dr. Homi Jehangir Bhabha, founder-director of TIFR, attached great importance to participation in the colloquia and he would invariably attend these and lead the lively discussion at the end of the colloquia. It was an exhilarating experience for me to attend the colloquia and learn about the exciting developments in different disciplines of physics. The West Canteen of TIFR, overlooking the Arabian Sea, was also a regular meeting place for exchange of views and lively discussion on new developments and discoveries in physics, as well as contemporary social and science issues.

In December 1963, the Eighth International Cosmic Ray Conference was held in India in Jaipur. This meeting lasted for about 10 days and covered diverse areas of cosmic ray research. Since cosmic ray investigation was a dominant area of research in TIFR, there was a big delegation from the institute at the meeting and I was also a part of it. It was an exhilarating experience for me to listen to the talks by leading researchers from all over the world and interact with them in tea and lunch breaks. Dr. Bhabha had taken personal interest to ensure that the conference was a great success. He had successfully persuaded then Prime Minister of India Pandit Jawaharlal Nehru to grace the conference, address the delegates and meet them at the Conference Dinner. It was an electrifying experience to stand so close to the charismatic personality that Pandit Nehru was and listen to his remarks about science research and its relevance to India. The experiences from the Jaipur Conference are etched into my memory and I can still recall them vividly.

In the early sixties, there was an indication that a substantial fraction of helium in primary cosmic rays may be He^3 nuclei. Dr. V. K. Balsubrahmanyan (VKB) was a member of the HAS group who left TIFR to join NASA Goddard Space Flight Center (GSFC) just before I joined. VKB had come up with the idea of using a gas Cerenkov counter as an energy threshold detector to differentiate between He^3 and He^4. An instrument using a scintillation-solid Cerenkov detector, with a gas Cerenkov counter sandwiched between them, was developed by VKB, S. K. Roy and S. V. Damle (my senior colleagues) to measure He^3/He^4 ratio.

After the departure of VKB and S. K. Roy to USA, I was asked to work on this experiment along with George Joseph, who had joined the HAS group along with me. This instrument was successfully used in two balloon experiments in 1964 which yielded only an upper limit on the abundance of He^3 in cosmic rays (Agrawal et al. 1965a). In 1965, the solar activity was at its minimum level and hence fluxes of proton and helium nuclei were expected to be maximum. For accurate determination of flux of protons and helium nuclei, a series of three balloon experiments using scintillation - Cerenkov telescopes in coincidence mode were planned. George Joseph and I had the responsibility of conducting the experiments, which were carried out successfully. These experiments led to the accurate measurement of flux of protons with energy $> 15\,\mathrm{GeV}$ and helium nuclei of $> 7.5\,\mathrm{GeV\,nucleon^{-1}}$ (Agrawal et al. 1965b). Deep involvement in these cosmic ray experiments was a valuable experience for me in developing instruments for future for balloons, rockets and satellites.

My colleague S. V. Damle initiated the development of the spark chamber (SC) at TIFR with the idea of using it in cosmic ray research, but the project could not progress much due to technical issues. He entrusted this development work to me in 1965. With the able technical support provided by our group's engineers, I made a new SC using a different design and when we filled it with argon and applied 20 kV High Voltage (HV) pulse, muons and electrons produced by cosmic rays became visible. Over the next 2 years, I successfully developed large area (40 cms diameter) plastic scintillation and Cerenkov detectors (Sc-C). This led to my first publication in a journal titled 'Nuclear Instruments and Methods' (Agrawal & Kunte 1968). To correct for the position dependence of the pulse height from the detectors, two thin wall SCs were inserted between the Sc-C detectors to determine the position of each event and correct the pulse height. A new instrument was designed and fabricated to measure the abundances of heavier nuclei in primary cosmic rays using the Sc-C-SC telescope. It was flown in a balloon experiment from Hyderabad in 1967 but no useful results could be obtained as the 2 mcf volume balloon could carry the heavier instrument to a height corresponding to about $10\,\mathrm{g\,cm^2}$ of residual atmosphere, causing significant fragmentation of the heavier nuclei. There was no possibility of importing larger volume balloons and hence this experiment was put in cold storage.

The period of 1960–1990 was a time of great excitement in astronomy and astrophysics as many notable discoveries were reported which completely transformed our ideas of the origin, evolution and scale of the universe and its constituents. I term this period as the Golden Age of Astronomy. In 1962, with a rocket experiment, R. Giacconi and his team were looking for lunar fluorescent X-rays, but serendipitously discovered the first extra-solar cosmic X-ray source Scorpius X-1 (Sco X-1) (Giacconi et al. 1962). The true nature of the radio source 3C 273 as a quasar was deciphered by M. Schmidt who explained the puzzling optical spectrum of its counterpart as arising from its large red shift. The discovery of the first radio pulsars by Joceyln Bell and A. Hewish in 1964 happened around the same time and was explained as spinning neutron stars. In 1965, the detection of a whisper of the Big Bang event in the form of microwave background radiation at a temperature of 2.7 K put the Big Bang theory on a firm footing, explaining a host of phenomena. The detection of a burst of 12 neutrinos from the supernova (SN) explosion in the Large Magellanic Cloud (LMC), in 1987 known as SN 1987A by the Japanese experiment Kamiokande, is a landmark event in astrophysics, confirming the theory of stellar evolution and SN explosion. The most energetic burst of radiation in the universe, known as gamma-ray bursts (GRBs), was detected accidentally in 1967 but announced only in 1973, and remained a mystery till 1997 when the Italian satellite BeppoSAX identified a GRB from its X-ray and optical afterglow and showed it to be from a galaxy at red shift of 0.87. These discoveries created great excitement among astronomers.

3 X-RAY ASTRONOMY RESEARCH AT TIFR DURING 1967–1975 AND COLLABORATION WITH THE JAPANESE X-RAY GROUPS

When I joined TIFR, cosmic ray studies and nuclear physics were two major areas of research in physics at TIFR. There were three major cosmic ray groups which investigated primary and secondary cosmic rays using different detection techniques. A group led by Prof. B. V. Sreekantan studied very high energy cosmic rays (E> 10^{14} eV) using a variety of detectors like a cloud chamber, scintillation and Cerenkov counters, etc., to detect and measure the number and energies of secondary cosmic rays produced by air showers, resulting from interactions of primary cosmic rays in the atmosphere. In 1965, Sreekantan took sabbatical leave and joined the cosmic ray group of Prof. Bruno Rossi at Massachusetts Institute of Technology (MIT), which was engaged in similar research. Rossi was also involved in the discovery of the first cosmic X-ray source Sco X-1. Some members of his group were also engaged in the joint American Science and Engineering (ASE)-MIT rocket experiment to measure the size and location of Sco X-1 precisely, to identify its optical counterpart. It was an exciting time at MIT and Sreekantan also joined this experimental team. Based on the precise position of Sco X-1, it was identified with a 13th magnitude star. The optical identification led to the startling conclusion that Sco X-1 was truly an X-ray star as its X-ray luminosity was ~ 1000 times its optical luminosity and was estimated to be $\sim 10^{36}\,\mathrm{erg\,s^{-1}}$. What process was at work in Sco X-1 producing X-rays at such prodigious rate remained a puzzle till the launch of the first X-ray satellite Uhuru in 1970. Uhuru discovered, in 1971, that the X-ray intensity of source Cen X-3 was varying with a 4.8 s period and hence it was an X-ray pulsar in a binary system. Discovery of a second X-ray pulsar Her X-1 followed and this was also found to be a binary star. These discoveries led to the conclusion that X-ray binaries like Sco X-1 are powered by accretion of matter from their optical companion in the deep gravitational well of a neutron star or a black hole.

When Sreekantan returned to TIFR in 1967 after participating in X-ray rocket flight experiments, he was filled with excitement at the prospect of initiating research at TIFR in a new and largely unexplored waveband. He was aware that George Clark at MIT had made a balloon experiment and was successful in detecting X-rays in 20–50 keV from the well known supernova remnant (SNR) the Crab Nebula. Sreekantan immediately realised that TIFR had the required facilities and knowhow to undertake hard X-ray astronomy research using balloon borne instruments.

Dr. Homi Bhabha had suddenly passed away in a plane crash in 1966 and Prof. Menon had been designated as the new Director. Sreekantan knew Menon well and was confident that Prof. Menon would support him in his new venture into a relatively unexplored region of astronomy. He discussed his proposal with Prof. G. S. Gokhale, head of the HAS group who wholeheartedly supported it. Sreekantan then came to our laboratories and explained his plans for conducting balloon experiments to study X-rays in 20–150 keV from selected sources visible over Hyderabad. He emphasised that since Hyderabad is located close to the geomagnetic equator (Geomagnetic latitude 8°N), cosmic ray produced atmospheric X-ray background will be minimum, giving significant advantage in sensitivity. He then enquired if any of us were interested in this programme.

I jumped at this exciting opportunity for research in a virgin area and joined the new X-ray payload team. Ravi Manchanda also opted for the X-ray team. Over the next year we worked frantically to design and fabricate a hard X-ray telescope consisting of an NaI (sodium iodide) detector with about a $100\,\mathrm{cm}^2$ area surrounded by a cylindrical plastic scintillator anti-coincidence shield to reject cosmic rays. The telescope was mounted on an oriented platform driven by a DC motor controlled by a magnetic flux gate sensor to track the target sources. The instrument weighing about 100 kg was ready for balloon flight by the middle of 1968 (Agrawal et al. 1971).

The design and fabrication of the plastic balloons were carried out in-house by a Plastic Balloon Fabrication (PBF) group in TIFR. The balloon flights were carried out from the ground of Osmania University at Hyderabad during November-December and March-April when stratospheric winds were favourable. I soon learnt, to my dismay, that for many years the TIFR balloon flights were failing, as balloons used to burst at 15 to 20 km altitude in the troposphere (which has a temperature of –80° to –90° C near equatorial latitudes). Fortunately, Prof. G. S. Gokhale, who headed the HAS and PBF groups, came up with the idea of making black polyethylene balloons by adding carbon black in the resin used to extrude the polyethylene film. In the daytime balloon flights, the balloon got warmed up due to heating by absorption of sunlight and survived the journey through the troposphere. Bright X-ray sources like Sco X-1, Cygnus X-1 (Cyg X-1), etc., were at meridian transit during the night or early mornings during the balloon flight windows. We had to make night flights requiring import of balloons, which was approved by Menon.

The first successful experiment was done on 1968 December 22 to observe the time variability of Sco X-1 and its energy spectrum. During about 2 h of observation, the intensity of Sco X-1 dropped by a factor of about 2 and then recovered to almost the original value. The spectral data showed that in 20–40 keV, the energy spectrum was fitted well by a thermal bremsstrahlung model with kT ~ 5 keV. Above 40 keV there was spectral flattening due to possibly a non-thermal spectral component. This result appeared in Nature (Agrawal et al. 1969) .

Fig. 1 The author (*on the extreme left*) engaged in testing the PCs for the rocket borne experiment at TERLS in early 1972 to measure X-ray spectra in 0.5–10 keV.

There were reports of detection of millisecond scale pulsations from the enigmatic bright source Cyg X-1. We refurbished the payload and made a balloon flight targeting Cyg X-1 to detect pulsations as well as the energy spectrum. No pulsations were detected and a stringent upper limit was set on their presence (Manchanda et al. 1971). In another experiment in 1969, Cyg X-1 was again studied and rapid flux variations over tens of minutes as well as the occurrence of an X-ray-flare were recorded. These results were published in two separate papers in Nature (Agrawal et al. 1971) and Nature Physical Science. Over the next few years, a series of balloon experiments was conducted to study bright X-ray sources and also the DXCB, leading to more results and publications.

Sreekantan also initiated rocket flight experiments to study spectra of Sco X-1, Tau X-1, etc., in 0.5–10 keV using Centaur rockets. I worked on developing Proportional Counters (PCs) for the experiment involving V. S. Iyengar for whom this was the thesis project. We went to Thumba Equatorial Rocket Launching Station (TERLS) in early 1972 for the launch, but due to a serious technical snag in the instrument, had to postpone the flight to next year. I left in July 1972 to join the California Institute of Technology (Caltech) and my association with this programme came to an end. The rocket instrument under integration at TERLS is shown in Figure 1.

By the end of 1970 there was enough new research material with me to write my Ph.D. thesis. Intensity variations and energy spectra of Sco X-1 and Cyg X-1 and their interpretation formed the core topic of my thesis. I submitted it to Mumbai University in the latter half of 1971 and was declared eligible for the Ph.D. (Physics) degree in April 1972.

In 1968, Prof. S. Hayakawa of Nagoya University, Japan proposed a collaborative balloon experiment to study the energy spectrum of diffuse cosmic X-ray background (DCXB) in the 100 keV to 1 MeV band. The X-ray instrument was to be built at Nagoya University with participation of TIFR and the balloon flight was to be conducted by TIFR from Hyderabad. The proposal was given the green light by TIFR and I was deputed to Nagoya University for 3 months, to work with them on the development of the instrument. I was part of Prof. Hayakawa's group, interacting and working with Prof. Y. Tanaka and F. Makino. It was a great learning experience for me as the style and work culture in these Japanese laboratories were very different from those in TIFR.

There were no engineers or technical staff at the Nagoya laboratory to assist one in the fabrication of electronics or detector parts - everything had to be done by the scientists themselves. The X-ray instrument was built, tested and shipped to TIFR in late March. Tanaka and Makino visited TIFR for the balloon experiment which was successfully conducted from Hyderabad in April 1969. Data from the experiment provided the spectrum of DCXB (Danjo et al. 1971). This collaboration led to another proposal to jointly study correlated X-ray and optical intensity variations in Sco X-1 by simultaneous observations in X-ray with a balloon borne experiment and in optical by a ground based telescope. This proposal included the Institute of Space and Astronautical Science (ISAS) and Nagoya University from Japan and TIFR from India.

Two campaigns for simultaneous observations of Sco X-1 from Hyderabad were successfully carried out in 1971 and 1974 and were led by Prof M. Matsuoka from ISAS. These experiments demonstrated co-related simultaneous intensity variations in the Optical and X-ray bands, and the results appeared in two papers (Matsuoka et al. 1972). These collaborations led to development of academic exchanges and visits between ISAS, Nagoya University, RIKEN and TIFR. I was a Visiting Professor at ISAS in 1984 and at RIKEN in 1997. My two students, Dr. B. Paul and Dr. S. Naik, worked at ISAS as JSPS post-doctoral fellows (PDFs). Another student of mine, Dr. Priyamvada Bisht, was a PDF at RIKEN with Prof. M. Matsuoka.

4 POST-DOCTORAL YEARS AT CALIFORNIA INSTITUTE OF TECHNOLOGY AND INVOLVEMENT IN HIGH ENERGY ASTRONOMICAL OBSERVATORY-A2 EXPERIMENT

The Twelfth International Cosmic Ray Conference (ICRC) was held in December 1971 at Hobart, capital of the Australian state of Tasmania. I was deputed to the conference to present our hard X-ray results on Cyg X-1 and other sources which I highlighted in my talk. After the conclusion of the session, I happened to meet a young scientist from USA, Professor Gordon Garmire of Caltech, during the tea break. He said that he found our results interesting and enquired about my plans after the completion of my Ph.D. I learnt from him that he had collaborated with Sreekantan at MIT in X-ray experiments on Sco X-1 as well as in cosmic rays. He said that he and Dr. Elihu Boldt of GSFC were Co-Principal Investigators of a proposal to study the spatial structure and spectrum of DCXB over a broad band of 0.1–60 keV and the proposed instrument designated as High Energy Astronomical Observatory - A2 (HEAO A-2) experiment payload will be built jointly by GSFC and Caltech for launch in 1977. He said that he may have a PDF position available from the middle of 1972 and asked if I would be interested in applying for it. I was overjoyed at the prospect of working for a satellite-borne experiment. After returning to Mumbai, I wrote to Garmire with my CV and in May 1972, I received the offer of Research Fellow (a PDF position) in the Physics Department of Caltech. I landed in Los Angeles with my wife Rama and one year old daughter Rashmi in the early evening of July 3 and took a bus to Pasadena. We stayed in a motel within walking distance of Caltech.

In the next few days, I became familiar with the technical details of the A-2 instrument and responsibilities at Caltech. Two Low Energy Detectors (LEDs) and their thin X-ray entrance windows, collimators, magnetic brooms to sweep away low energy electrons, gas filling and control system, inflight low energy calibration sources and front-end electronics, were to be developed at Caltech. Dr. Guenter R. Riegler at Bendix Corporation in Ann Arbor, and previously a Research Fellow with Gordon, was involved in the design of the LED sub-systems. In the next year, a lot of progress was made in evolving the final design and testing of prototype units before taking up the fabrication of flight hardware.

Development of pin-hole free thin polypropylene windows was especially challenging. Propane gas at a pressure of about 300 torr was the counting gas for the LEDs. Gas filling and control system was successfully developed at Caltech with support from the GSFC team. Every three months, progress on development of the instruments was reviewed either at GSFC or at Marshall Space Flight Center (MSFC) in Huntsville, and I represented Caltech at a few such reviews. About a year after I joined, Gordon decided to take a sabbatical and the responsibility of the LED development lay with me. This was a crucial period as fabrication of the flight hardware was to begin.

Initially, I was apprehensive about whether I would measure up to the task, but soon I became confident and plunged wholeheartedly into the work. I attended several progress review meetings and felt that our progress was steady and appreciated. Elihu Boldt with his gentle manners and soft voice was a pillar of support and encouragement. I spent 3 years at Caltech working on the A-2 LED instrument. Along with this project, in the first year, I also got involved in two rocket flights launched from Australia to study Cen X-3 (Long et al. 1975) and DCXB below 3 keV. Side by side, I developed a position sensitive PC to record X-ray images at the focal plane of a precision machined and polished aluminium paraboloid-hyperboloid X-ray telescope (Agrawal et al. 1976).

During my last two months at Caltech, I was busy in the assembly and calibration of the collimators for the LEDs. All in all, I became familiar with the nitty gritty of the LEDs and fine technical issues and their resolution. I became well versed with the mechanical design of space hardware and vacuum systems and their tests and qualification. The experience and knowledge gained at Caltech on all aspects of space instrumentation proved most valuable when I returned to TIFR towards the end of 1975 and started rocket-borne soft X-ray astronomy experiments and the development of detectors for future Indian satellites. I greatly enjoyed the academic ambience and lively atmosphere at Caltech. It is a rather small school with undergraduate and graduate student population of about 2000, but it is ranked among the top 10 universities worldwide, thanks to the high quality and achievements of its faculty. In astronomy and physics, it is among the most coveted places. The Physics Research Conference every Thursday was a regular feature and well attended.

The HEAO-A2 experiment (Rothschild et al. 1979) was tested and qualified, and HEAO-1 was launched in August 1977. All four payloads on it performed well and yielded a wealth of data on the discrete sources as well as DCXB. The A-2 experiment operated for about one and half year, performed as expected, and led to several discoveries. Gordon Garmire was a generous person in recognising the contributions of colleagues. In recognition of our contributions to the A-2 experiment, he allotted 20% of LED data to Guenter and me.

Guenter Riegler had moved from Bendix Corp to Jet Propulsion Laboratory (JPL) to develop the gamma-ray spectrometer for HEAO-3. Guenter, with the backing of Gordon and Elihu, invited me to apply to JPL for an NRC-NAS Senior Resident Research Associateship (RRA) and work on science analysis of the LED data. I was awarded the RRA position at JPL and I joined it in July 1978. During my one and a half year tenure as RRA, Guenter and I worked on the identification of a bright soft X-ray source detected with the LEDs with the radio source PKS 2155–304, which had the characteristics of a BL Lac object and deduced its spectrum and variability (Agrawal & Riegler 1979).

We also studied the spectrum of another BL Lac, PKS 0548–322, (Riegler et al. 1979) and identification of another soft X-ray source with SNR MSH 11–54 (Agrawal & Riegler 1980). These results were published in a se-

Fig. 2 The author with wife on the Caltech campus in October 2013 during a personal visit to Pasadena.

ries of four ApJ Letter papers. A notable discovery during this work was the detection of a highly variable soft X-ray source H0139–68 from the LED data, determination of its position by Einstein Observatory (EO) which led to its optical identification with a 113 minute period AM Herculis like binary, now known as BL Hydri (BL Hyi) described in a paper in Nature (Agrawal et al. 1983). Looking back, I can say that my years at Caltech and JPL were among the most satisfying and scientifically fruitful periods of my research career.

The HEAO-2 satellite, which carried an X-ray imaging telescope developed by Giacconi and his group, was launched in November 1978 and renamed as EO. The X-ray telescope based on the use of paraboloid-hyperboloid mirrors for focussing 0.2–3.5 keV X-rays incident at grazing angle, used an Imaging Proportional Counter (IPC) for recording X-ray images with angular resolution of $\sim$ an arcminute and a High Resolution Imager (HRI) for resolution of about $5''$. The EO sensitivity was $\sim$ 1000 times better compared to the earlier satellite which used non-imaging detectors. This quantum leap in sensitivity enabled EO to detect distant quasars and coronal X-ray emission from Sun-like stars.

EO observing time was allotted based on peer review of the science merit of the proposals. I also made several proposals, most of which were granted observing time. One proposal concerned coronal X-ray emission from flare stars, most of which were dMe or dM stars. We studied about a dozen flare stars with EO and detected all in X-rays. We computed the X-ray luminosity ($\mathrm{L_X}$) and bolometric luminosity ($\mathrm{L_{Bol}}$) of all the X-ray observed flare stars and other late type stars. A plot of $\mathrm{L_X}$ versus $\mathrm{L_{Bol}}$ revealed a strong correlation between them, which is shown in Figure 3 (Agrawal et al. 1986). This important result has stood the test of time.

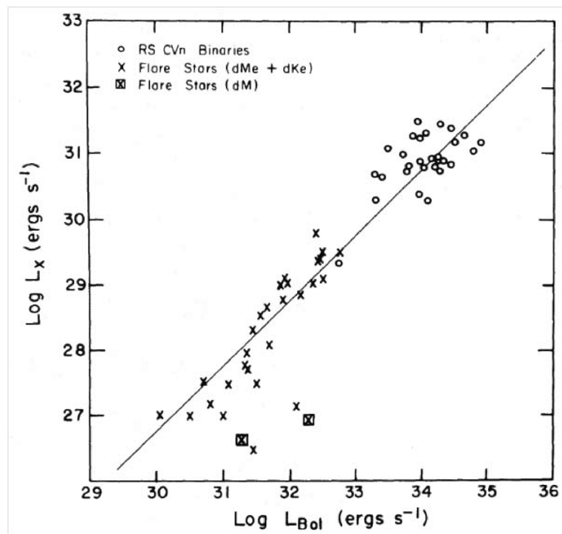

Fig. 3 Plot of X-ray luminosity versus bolometric luminosity for flare stars and regular period RS CVn binaries. The straight line corresponds to the best fit relation $\mathrm{L_X} = 10^{-3.22\pm0.22}\mathrm{L_{Bol}}$ (From Agrawal, Rao & Sreekantan 1986).

5 DEVELOPMENT OF NEW RESEARCH PROGRAMMES AND INDIAN X-RAY ASTRONOMY INSTRUMENT (IXAE) AT TIFR DURING 1980–2000

After returning to TIFR in September 1975, I noted that the group had oriented fully to research in astronomy. X-ray astronomy had been growing at a rapid pace with new discoveries being reported from the Uhuru satellite. X-ray emissions from major classes of Galactic and extragalactic sources were detected by Uhuru. The era of rocket and balloon experiments with modest sensitivity seemed to be coming to a gradual end. It was clear that the future of X-ray astronomy lay with satellite-based instruments. In 1975, India developed the Aryabhatta satellite with three payloads and it was placed in a near Earth orbit by a Russian rocket. Unfortunately due to a technical snag, the satellite ceased operation after 2 days.

The same year, India launched a satellite with a modest weight of $\sim$ 35 kg using a rocket developed by the Indian Space Research Organization (ISRO) called Satellite Launch Vehicle (SLV). An improved version of this rocket named Augmented Satellite Launch Vehicle (ASLV) with the capability of placing a 150 kg satellite in near Earth orbit was developed but failed in its mission on the first attempt. The next launch of ASLV with a 110 kg satellite was successful. This satellite could accommodate a science payload of 10 kg, which was not enough for an X-ray astronomy instrument that could produce new science.

It was obvious that an Indian satellite-borne instrument had to wait till a more powerful launch vehicle was realised. Meanwhile, I realised that a rocket experiment to map the spatial and spectral structure of the Soft Diffuse Cosmic X-ray Background (SDCXB) in boron and carbon transmission bands had the potential of providing new results. RH-560 rockets developed by ISRO could carry a 100 kg instrument to an altitude of about 400 km, providing exposure of $\sim$ 400 s. K. P. Singh (hereafter referred as KP) had joined as a new Research Scholar in the group and worked in this programme. My experience in making micron thick polypropylene windows coated with colloidal carbon and boron proved valuable in their fabrication by KP. Two soft X-ray detectors filled with propane and similar in many respects with the LEDs on HEAO A-2 instrument, along with the front end and signal processing electronics, were successfully developed and qualified. One rocket flight experiment was carried out in 1983. This experiment measured the structure and spectral distribution of SDCXB in 0.1–3 keV and constituted the Ph.D. thesis of KP (Singh et al 1983).

With no possibility of a satellite experiment for at least another decade, I initiated development of a new balloon instrument based on xenon - filled deep and large area PCs (effective area of $\sim$ 2500 cm^2 at 40 keV). A fully tested instrument ready for balloon flight is shown in Figure 4. In 1976, A. R. Rao (hereafter Rao) had joined as a Research Associate and he contributed very significantly to the design and realisation of the new Hard X-ray Balloon Instrument (Rao et al. 1986). Several balloon flights were made in the period 1983–1990 with the new hard X-ray instrument to investigate the spectral and timing characteristics of X-ray binaries like Cyg X-1, Cyg X-3, 4U 1907+09, etc. (Chitnis et al. 1993, 1998).

Results from these experiments and their modelling constituted the Ph.D. thesis of my research student Varsha Chitnis. The experienced gained in the design and development of this hard X-ray balloon instrument proved very valuable in the development of the Large Area X-ray Proportional Counter (LAXPC) Instrument for the first Indian Astronomy satellite (ASTROSAT). In the period 1985–1990, I initiated the development of a new X-ray Instrument for a satellite mission, with a sensitive area of about 1600 cm^2 to study time variability and spectra of X-ray binaries and other bright sources in 2–20 keV.

One argon-filled PC with effective area of $\sim$ 400 cm^2 and a 25 micron Mylar entrance window was fully developed and tested with its HV, charge sensitive preamplifier (CSPA) and electronic logic. The idea was that if an opportunity arises for a satellite experiment aboard an Indian mission, we should not be caught unprepared to avail such an opportunity. I wrote a detailed proposal jointly with the Space Astronomy group at the ISRO Satellite Centre (ISAC) led by Dr. Krishnan Marar for an Indian X-ray Astronomy Experiment (IXAE) with four co-aligned Pointed Mode Proportional Counters (PPCs) to fly aboard one of the satellites. No action could be taken on the proposal as ISRO was still working on developing a rocket with a heavier payload capability.

During 1987–1988, I visited the X-ray Astronomy Group of Martin Weiskopff at MSFC as a Senior NAS-NRC RRA. During about one and half year of my tenure at MSFC, Dr. Brian Ramsey and I worked on understanding which quench gases give the best energy resolution and gas gain for the Argon and Xenon filled Proportional Counters (XPCs) and what parameter decides this. We also investigated the Penning effect, and which gases show maximum effect and how this aspect can lead to improved energy resolution in PCs. Our work showed that gases having ionization potential (IP) just below the IP of the main filling gas show maximum Penning effect. These results were published in a series of four papers in NIM (Ramsey & Agrawal 1988; Agrawal et al. 1989).

In 1994, the first test flight of the Polar Satellite Launch Vehicle (PSLV) was a complete success. PSLV had the capability of inserting a $\sim$ 1000 kg satellite into a polar orbit at an altitude of about 800 km in near Earth orbit. It could place a satellite of $\sim$ 1500 kg in a 600 km near Earth orbit. PSLV was the ideal launch vehicle for a series of Indian Remote Sensing (IRS) satellites. The next satellite IRS-P3 was planned to be launched in March 1996 and it could accommodate a piggyback payload of about 50 kg mass. In 1994, Dr. Kasturirangan (hereafter referred as Dr. Rangan) succeeded Dr. U. R. Rao as the ISRO Chairman. I knew him well and took up the possibility of inclusion of IXAE on the IRS-P3 satellite.

Dr. Rangan was quite enthusiastic about the proposal and said that if we can deliver the tested and space qualified IXAE instrument in 18 months, it could be included on IRS-P3. ISRO will provide limited observing time by pointing the satellite at the sky and capability for pointing and tracking of the X-ray targets will be provided. We accepted the challenge and worked frantically, at breakneck speed, for the fabrication of the PPCs and associated front end system. ISAC took responsibility for the fabrication of signal processing electronics and interface for data transmission. The detectors and associated electronics were fab-

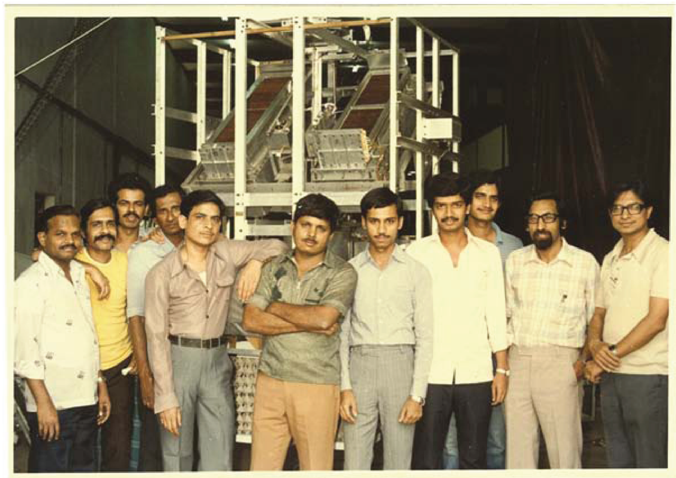

Fig. 4 The author (extreme right) with his team for conducting a balloon experiment with the Xenon-filled Multilayer Proportional Counter (XMPC) instrument shown in the background, at the TIFR Balloon Facility, Hyderabad in March 1986. The two XMPCs are visible on the orientable platform.

Fig. 5 The wired anode frame assembly for the Pointed Proportional Counter (PPC) of the IXAE ready for installation in the detector housing is being examined by the author (*front*) in the detector assembly laboratory at TIFR in June 1995.

ricated, tested for their space worthiness and delivered in time for integration with the satellite.

The IRS-P3 satellite with the IXAE instrument was launched on 1996 March 21 by PSLV into a polar orbit at 800 km altitude. A month after the launch, the satellite was oriented to point at the sky and IXAE HV and electronics were switched on. The IXAE PPCs were pointed at the well-known black hole binary Cyg X-1 and when the data were read after the ground pass, the count rates were as expected from Cyg X-1. There was jubilation all around, as it showed that gas-filled PPCs were functioning normally. We were provided a 2 month observation period.

Polar orbit is the worst possible orbit for an X-ray mission as the satellite will spend lot of its time in the South Atlantic Anomaly (SAA) region. Background will be variable with latitude. Only about 20 minutes of useful data can be obtained in an orbit. We decided to make the best use of whatever time we could get for observing sources. A new bright X-ray transient, now known as GRS 19015+105, had been detected but its nature was unknown. We decided to study this source with IXAE by observing it continuously for about a month.

The data proved to be a gold mine of new results. Analysis of the data revealed the presence of quasi-periodic oscillations (QPOs) at about 0.7 Hz, with QPO frequency drifting with the intensity of the source. The X-ray light curve revealed quasi-periodic bursts occurring every ~ 50 s having slow rise but fast decay, which was puzzling. The shape, duration and frequency of the bursts changed with time. The luminosity of the bright object was super Eddington. We interpreted the slow rise time of the peculiar periodic X-ray bursts as time taken by the matter ejected from the black hole accretion disk to reach the innermost region close to the event horizon of the black hole. We suggested that the fast decay of the bursts was due to infall and sudden disappearance of the hot matter behind the event horizon. This result appeared as an ApJ Letter in 1998 (Paul et al. 1998).

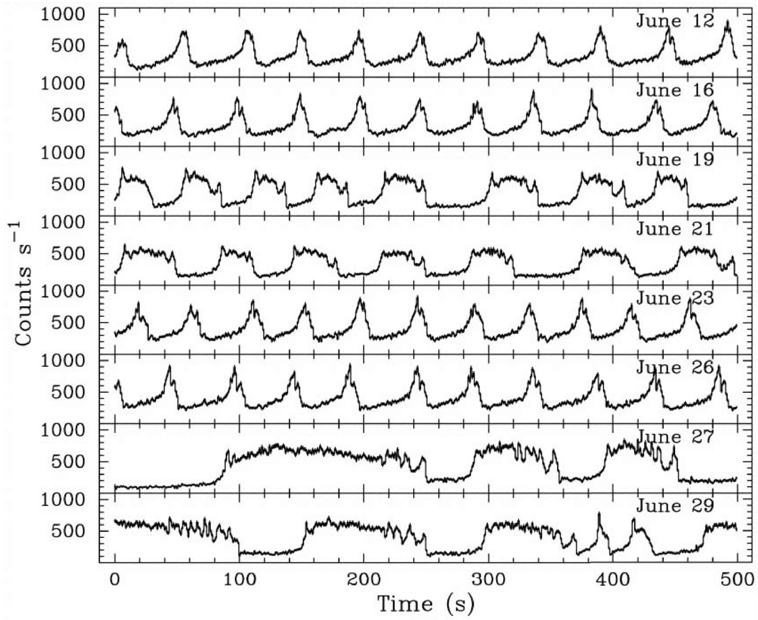

Fig. 6 X-ray bursts from the micro-quasar GRS 1915+105 detected with the IXAE (Paul et al. 1998).

More detailed analysis of the X-ray bursts from GRS 1915+105 was carried out by Yadav et al. (1999) which demonstrated richness of variability and uniqueness of this enigmatic black hole binary.

During the course of the next 4 years, about 20 X-ray binaries and other objects were studied to investigate their temporal characteristics. Several interesting results on variations in the spin and orbital periods were inferred, with the most notable being variation in the 4.8 hour periodicity of Cyg X-3 (Singh et al 2002). By the 5$^{\rm th}$ year after launch, thrusters used to orient the satellite ran out of fuel and hence the IXAE was switched off. IXAE results formed the basis of the Ph.D. theses of Biswajit Paul and Sachindra Naik. About 20 research papers were also published based on results from IXAE.

6 GENESIS OF ASTROSAT, ITS DEVELOPMENT, LAUNCH AND OPERATION

The success of the IXAE was a big morale booster and it gave me confidence that we can design and develop detectors that will survive the harsh launch environment and function in the adverse conditions at an altitude of 600 km. I felt confident that we can conceive and fabricate a complex and bigger instrument with sensitivity comparable to or better than that of other satellite instruments in operation. I made the preliminary design of a large area (10 000 cm^2) PC based instrument for the spectral and temporal studies of X-ray binaries and other cosmic X-ray sources in 2–80 keV. I wrote a brief proposal describing salient features of the instrument, its development and fabrication plan, and its international competitiveness in terms of expected science results. I submitted it to Dr. K. Kasturirangan, Chairman of ISRO through TIFR Director Prof. V. Singh.

I was pleasantly surprised at the prompt response from Dr. Rangan, who suggested that I convene a meeting of Indian astronomers interested in proposing payloads for space astronomy experiments. The meeting was held in July 1996 at ISRO Headquarters in Bengaluru. About 30 astronomers working in different wavebands of astronomy from a large number of science institutions participated in the meeting. Over the course of the next 2 days, a variety of proposals in infrared, optical, ultraviolet (UV), X-ray and gamma-ray astronomies were presented and discussed critically. It became clear from the proceedings of the meeting that there was great enthusiasm and interest to participate in the future astronomy mission of ISRO. There seemed to be a broad opinion that the planned satellite should have a broad spectral coverage.

The Chairman constituted two Working Groups (WGs), one for examining proposals in X-ray and gamma-ray astronomy, and the second to review proposals in infrared, optical and UV astronomy. The groups were mandated to critically review all the proposals for science objectives and their international competitiveness, technical soundness, development plan, capability and resources of the proposers to realise the instruments. The WGS had several meetings over the next 2 years and short listed viable and technically sound proposals, The two WGs held a joint meeting chaired by me in late 1998 to discuss and evolve a final list of proposals to be recommended to ISRO for a full fledged astronomy satellite. The WGs had converged to the view that the mission should aim at a niche area in which it will have unique capability not available in any other operating astronomy satellite.

Fig. 7 Celebration of 5 years of Operation of IXAE and 60$^{\text{th}}$ birthday of the author at ISRO Satellite Tracking and Command (ISR0-ISTRAC) Centre in Bangalore in April 2001. Dr. K. Kasturirangan, Chairman ISRO presenting a memento to the author.

A multi-wavelength mission with broad spectral coverage by a suite of co-aligned instruments covering optical, near UV (NUV), far UV (FUV), soft X-ray and hard X-ray bands met the objectives of the mission. The principal instrument was chosen to be a cluster of four similar LAXPCs with about $1^\circ \times 1^\circ$ field of view (FOV) sensitive in 2–80 keV with an effective area of about $10\,000\,\mathrm{cm}^2$ to be built by my group at TIFR. A paraboloid-hyperboloid geometry based Soft X-ray Telescope (SXT) using thin foil mirrors, similar to that used in the Japanese satellite ASCA, with an X-ray CCD as the focal plane detector to record images and spectra of X-ray sources in 0.3–8 keV proposed by KP from TIFR, was chosen for coverage of the soft X-ray band.

A proposal from the Indian Institute of Astrophysics (IIA) by N. K. Rao, J. Murthy and A. Pati for an Ultraviolet Imaging Telescope (UVIT) based on the use of twin coaligned telescopes, one covering optical and NUV and the second sensitive in FUV, was the third instrument for broad spectral coverage. The three instruments, with their view axes coaligned, were located on the top deck of the satellite. A Scanning Sky X-ray Monitor (SSM) proposed by the ISAC group to monitor variability of sources and detect new transients was also chosen to be mounted on a side of the satellite. Details of the proposals for the four chosen instruments were presented to Dr. Rangan who appeared happy with the choice. He requested me to be the Principal Investigator (PI) and write a detailed proposal on behalf of the institutions involved for the proposed satellite providing development plans, teams responsible for the realisation of the payloads and schedule, cost, etc.

I started preparing the proposal but was interrupted by a sudden new development in the institute. The National Centre for Radio Astrophysics (NCRA) at Pune, a unit of TIFR created to design and set up Giant Metrewave Radio Telescope (GMRT), was in an advanced state of completion. The GMRT was conceived and designed by Prof. G. Swarup who also led it as Centre Director till his superannuation. He was succeeded by Prof V. K. Kapahi who was overseeing the progress of GMRT. In early 1999, Kapahi developed a serious illness and passed away in March 1999. His sudden departure created a vacuum at the top level in NCRA at that critical juncture.

Prof. S. Jha who became TIFR Director in 1997, asked me to move to NCRA, Pune as its Centre Director. Though I was not too enthusiastic about going to NCRA, considering the urgent need of completing construction of the GMRT and commencing its operation, I agreed to the proposal and joined NCRA in late March 1999. The ASTROSAT proposal was put in cold storage for the time being. I remained at NCRA for a full year and got into the nitty-gritty of various technical and managerial issues and tried my level best to resolve them. In March 2000, I conveyed to the Director that NCRA is now stabilised well and GMRT is shortly becoming fully operational, hence I would like to return to Mumbai. NCRA academic and technical staff requested me to continue as Centre Director but I expressed my inability, as I had a commitment to lead ASTROSAT.

I resumed work on the ASTROSAT proposal, completed it by early May 2000 and submitted it to Prof. Jha. He forwarded the proposal to ISRO Chairman with his recommendation and assurance that TIFR will provide all the facilities and support for its execution. The ISRO Chairman decided to have the proposal reviewed by leading space scientists and astronomers in the country. The review was held in September 2000 at TIFR and attended by the invitees. Before the review, Prof. Rao approached me and said that he wants to develop a cadmium zinc telluride (CZT) array of $\sim 500\,\mathrm{cm}^2$ effective area equipped with a Coded Aperture Mask (CAM) for low resolution hard X-ray imaging and spectroscopy in 10–100 keV. After some thought, I felt that it will be nice to have an instrument with a new generation solid state detector. I agreed to replace one of the LAXPCs with the CZT Imager (CZTI) if it was approved by the ISRO Chairman. I made a detailed presentation about the objectives of ASTROSAT, its unique Multi-wavelength (MW) capability and realization plans of the payloads. There was a detailed and critical discussion about all aspects of the mission and at the end, the ASTROSAT mission was endorsed by all the participants. I emphasised that ASTROSAT can place India at the forefront of research in experimental high energy astrophysics.

With the active involvement of Dr. George Joseph, a noted space scientist and ex-Director of the Space Application Centre (SAC), a condensed version of the ASTROSAT proposal was prepared for consideration and approval by the Space Commission. Some time near the end of 2000, the Space Commission approved the development plans of ASTROSAT payloads and also agreed to provide seed money for initiating work on the instruments. In 2003, ISAC Director Dr. P. S. Goyal appointed Mr. Koteswara Rao, an experienced engineer, as the Project Director of ASTROSAT and entrusted him to prepare a detailed Project Report for the approval of Government Of India. I provided the required inputs and the Project Report of ASTROSAT was submitted in the middle of 2004 and the ASTROSAT Project was approved by the Government in October 2004.

There were many challenges involved in the realisation of LAXPCs and the other four payloads which I have discussed in detail in Agrawal (2016, 2017). Design and creation of infrastructure for development of instruments at TIFR commenced in 2001. A 1.5 m diameter $\times 1.5$ m length Thermovac Chamber was set up to test and qualify LAXPCs. A ten thousand class large clean room was set up for the wiring and assembly of LAXPC anode frames and other components like collimator assemblies. This included careful wiring of anode frames with 37 micron diameter anode wires and 50 micron size Be-Cu cathodes. There were about 1300 wires under tension in each detector and loosening or breaking of a single wire could lead to HV failure. Mechanical fabrication of detector and collimator housings from blocks of aluminium alloys by milling on CNC machines was a complex and time consuming job. The collimator housing had two co-aligned collimator assembles, a Window Support Collimator (WSC) of crossed aluminium slats supporting 50 micron thick Mylar film, at a pressure of 2 atmosphere and a Field of View Collimator (FOVC) above WSC, which made its fabrication challenging. FOVC had to be lightweight and hence it was made from five layers: a 50 micron thick tin foil with 12.5 micron copper layer on either side followed by 50 micron aluminium alloy film on either side. The five layers have to be glued with a space grade epoxy and cured and outgassed for 15 days in vacuum, followed by cutting of slits by laser or water jet in each piece of FOVC slats. This was the most difficult work and it took nearly 4 years to make, align and install in the housings (Roy et al. 2016).

Fig. 8 Thirty-seven Micron diameter gold–plated stainless steel wires under tension were used for the anodes.

The SXT development was even more challenging as we had no prior experience at making mirror foils or a CCD camera. KP successfully met this challenge and accomplished fabrication of the SXT telescope mirror assembly which gave about 3–4 arcminute angular resolution. X-ray CCDs were not readily available and we lacked experience at their operation and characterization. University of Leicester (UoL) in UK, which had expertise in developing a CCD camera, was approached and they agreed to collaborate in fabricating the CCD camera with front end electronics for the SXT. An MOU was signed between TIFR and UoL for the joint development of an X-ray CCD camera for the SXT. For its contribution, UoL was guaranteed 3% of ASTROSAT observing time.

Development of the UVIT instrument was the most challenging among all the payloads. Since progress in evolving the design and development plan of UVIT was tardy, Prof. S. N. Tandon of Inter-University Centre for Astronomy and Astrophysics (IUCAA), who is an expert in the design of telescopes and optics in India, was requested to lead the realization of UVIT. In IIA there was neither experience in making UV optics nor in making photon counting imaging UV detectors. The mirrors of the twin UV telescope were successfully made by the Laboratory for Electro-Optics Systems (LEOS), a unit of ISRO. An agreement was signed between the Canadian Space Agency (CSA) and ISRO under which CSA took responsibility for supplying the photon counting detectors with complete signal processing electronics for the twin telescope of the UVIT. The CSA was provided 5% observing time on ASTROSAT in lieu of its contributions.

The CZTI instrument also faced many technical issues. This included achieving an energy threshold of 10 keV in the CZTI array, fabrication of CAMs, realization of low noise electronics, etc. Most of these were resolved but an energy threshold lower than 25 keV could not be realised.

All the five instruments went through shock, vibration, thermal and vacuum tests and were delivered for integration with the satellite one by one starting from 2014. The five payloads weighed 855 kg and total mass of ASTROSAT at launch was 1513 kg. By 2015, the fully assembled ASROSAT satellite was ready for tests before shipment to the launch site. On 2015 September 28, ASTROSAT was launched from Satish Dhawan Space Centre by a PSLV-C30 XL rocket into a circular orbit with altitude of 650 km and orbital inclination of 6 degree. When the successful insertion of ASTROSAT in its orbit was announced, there was great jubilation and applause as it was the culmination of 15 years of work.

The instruments were turned on one by one. The LAXPCs HV was switched on after lapse of about a month in orbit. The detectors seemed to be working well as indicated from the count rates. All the instruments were turned on and seemed to be performing as expected. The initial 6 months were for payload performance verification phase. Following it, Payload Guaranteed time observations were scheduled. After the first 2 years, ASTROSAT observing time is now available on science merit of peer reviewed proposals. More than 500 cosmic sources have been observed. ASTROSAT is now nearing completion of 4 years of operation in orbit. The instruments are broadly performing well except for some failures. One of the three LAXPCs has leaked and was turned off in the 3rd year and the Visible and NUV channel of UVIT has ceased operation. Many interesting results have emerged and appeared in publications in journals. Some of the early results have been highlighted by Agrawal (2016). A wealth of data on imaging, timing and spectral features has been gathered from different classes of X-ray and UV objects, which are at various stages of analysis. I am confident that in the next few years many more interesting results will emerge from ASTROSAT.

7 INVOLVEMENT IN OTHER NATIONAL SCIENCE PROGRAMMES DURING 1990 – 2010

TIFR celebrated 50 years since its founding in 1996. To commemorate this event, a series of conferences was held in different areas of physics and related subjects. I had the prime responsibility of organizing an International Conference in High Energy Astrophysics planned jointly by the Dept. of Astronomy and Astrophysics and Dept. of High Energy Physics, which included cosmic ray and TeV gamma-ray research. Selected leading researchers from abroad were invited to deliver talks. The meeting provided a good opportunity to assess our research programmes in an international context. I presented preliminary results from IXAE on IRS-P3 which were well received.

In 2000, ISRO Chairman constituted a Lunar Task Force (LTF) to do an in depth evaluation of technical issues for an Indian science probe to orbit the Moon. LTF was mandated to prepare a detailed technical report on a Moon mission, its main science goals and the instruments required to achieve them. The Moon mission was later named Chandrayaan-1. The LTF was chaired by Dr. George Joseph, ex-Director of SAC and it included Dr. N. Bhandari of PRL, the prime proponent of the Moon mission, Mr. Thyagarajan, Project Director for remote sensing satellites, myself and several other experts from other ISRO Centres. One of the objectives of the Moon probe was to map abundances of low Z elements on the surface. I was asked to design X-ray spectrometers for identification of elements and their abundances. I outlined the design of a Low Energy X-ray Spectrometer based on using Swept Charge X-ray CCD which needs only moderate cooling to about –20° to –30° C. These were used in SMART, the ESA Moon mission. I also suggested a High Energy X-ray Spectrometer using a CZT array detector to study scattered high energy X-rays. Both instruments were selected for Chandrayaan-1. The Moon satellite was placed in a 200 km lunar orbit by PSLV and worked well for about eight months, producing many new results, with the most important being detection of water molecules beneath the lunar regolith. Success of Chandrayaan-1 gave a big boost to planetary research missions advocated by ISRO. Mangalyaan sdevelopment was taken up by ISRO with renewed vigor.

The Chairman of ISRO had constituted an Advisory Committee on Space (ADCOS) to advise him on space science proposals for future ISRO missions. I served as a member of ADCOS during 2008–2018 and contributed to critical review and selection of payload proposals for Chandrayaan-2, Mangalyaan, the Aditya L1 mission and small satellite proposals. I also served on payload selection committees for the above missions. Serving on ADCOS was a pleasant and satisfying experience.

During 1998–2006, I was nominated Chairperson of Technical Problems of Scientific Ballooning by COSPAR. I organised balloon symposia at two COSPAR meetings and tried to rejuvenate them by bringing new balloon experimenters to the symposium. The balloon experiments serve as an excellent training ground for young researchers to learn about space instrumentation. The balloon symposia elicited good response and encouraged young experimenters to learn about instrumentation.

I have been a member of the Governing Council (GC) of Aryabhatta Research Institute for Observational Sciences (ARIES) since its founding in 2004. Then Director of ARIES, Dr. Ramsagar, proposed in the GC that

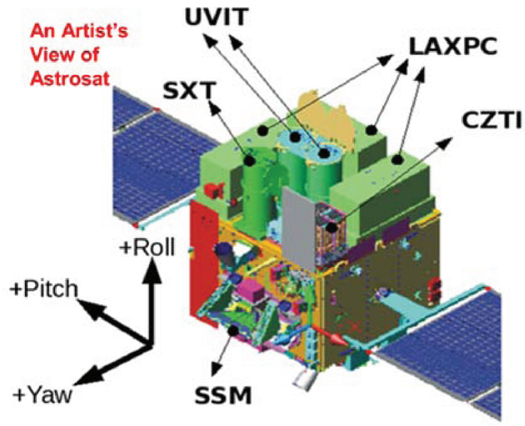

Fig. 9 Schematic view of the ASTROSAT satellite. The four instruments on the top deck with their view axes aligned along the roll axis are LAXPC, SXT, CZTI and UVIT. The SSM is mounted on the side panel.

Fig. 10 Fully assembled ASTROSAT satellite ready for qualification tests in the Integration Laboratory of ISRO Satellite Centre, Bangalore in May 2015. The four science instruments can be seen on the top deck of the satellite with their view axes coaligned along the roll axis of the satellite.

for meaningful and competitive research by ARIES a new technology telescope with at least 4 meter aperture was needed. I strongly supported it as I felt that without a new and modern telescope with larger size, ARIES has no future in astronomy research. There was a concern in the GC as to whether ARIES has the necessary skilled scientists and engineers to operate and maintain a new technology telescope. The Director convinced the GC that ARIES staff will be able to meet the challenge and the GC approved the proposal.

It appointed a Project Management Board (PMB) with me as Chairperson and Prof. G. Srinivasan as Vice-Chairman. After a lot of surveys and site characterization, ARIES had found a suitable site called Devasthal about 50 km away, at about 8000 ft altitude which has about 230 clear nights per year and very good seeing of $\leq 1''$. The contract for the design, fabrication and installation of a 3.6 meter size thin mirror telescope with active optics was awarded to the Belgian company AMOS. The project went through many difficulties that delayed it by $\sim$ 2 years. Completion of telescope enclosure and dome building was delayed by more than a year due to inexperience of the contractor which resulted in storage of the telescope parts. The telescope was finally assembled and installed in March 2016. It is now operational but from time to time faces technical failures of some sub-systems and components. The PMB held more than 30 meetings during 2006–2018 and provided guidance and advice on resolving technical and management problems. The PMB played a very active role in making the telescope operational and resolving technical problems. It gives me satisfaction that I could play a useful role in realization of the Devasthal Optical Telescope (DOT). Members of the PMB contributed to all aspects of the project, including providing guidance to the staff in developing focal plane instruments. I feel happy that I could play a role in the creation of a new observation facility with the largest optical telescope in India.

Acknowledgements During my long career in science, I have immensely benefitted from support and encouragement from my scientific colleagues, collaborators, students and technical staff working with me. I gratefully recall the role of my mentor Prof. B. V. Sreekantan who introduced me to X-ray astronomy and supported my research programmes - I owe my induction in astronomy to him. I also recall late Prof. G. S. Gokhale who gave me full academic freedom for development of instruments in cosmic rays in my early years. I learnt instrumentation and electronics from my senior colleague late Prof. S. V. Damle and I am thankful to him. I had fruitful collaboration with my colleague George Joseph in the early years of cosmic ray studies. Dr. George Joseph moved to the Space Application Center in Ahmedabad and pioneered the development of remote sensing cameras for satellites. In 2000, I had the pleasure of working again with him when I also served on the LTF. I am thankful to George for his trust in me. I recall the contributions of my colleague Ravi Manchanda with whom I had long collaboration, especially in balloon experiments and who succeeded me to lead the LAXPC instrument team after my retirement. Working on rocket-borne soft X-ray experiments with KP was a pleasure. I also benefitted from discussions and contributions of my research students Rao, Jyoti Singh, Varsha Chitnis, Priyamvada Sarswat, B. Paul, Sachindra Naik and K. Mukerjee. Many of them are now leaders in their own right and leading new satellite experiments. I was co-guide of Jayashree Roy and appreciate her contributions to ASTROSAT data analysis. It was a pleasure to work with J. S. Yadav and M. Vahia, who joined me in the late nineties. Among the scientific staff I acknowledge the outstanding contributions of the electronics engineers D. K. Dedhia, Parag Shah and late M. R. Shah who worked with me on many balloon and satellite instruments and were instrumental in the design and development of the electronics. Complete LAXPC electronics and programmable HV system, which are performing well in orbit, were realised mainly by D. Dedhia and P. Shah with contributions of P. Madhavani who joined the LAXPC team later. Among the technical staff, I thank J. Parmar, D. Pawar. V. Gurjar, the late Mohite and A. Kurhade for their contributions to LAXPC instrument and other projects. I benefitted from collaboration with the Space Astronomy Group at ISAC in the IXAE project and thank Dr. Marar for his help and contributions.

ISRO Chairman Constituted "ASTROSAT Progress Monitoring Committee" (APMC) to monitor progress of development of instruments and provide advice and guidance for resolving technical problems. Dr. George Joseph was the Chairperson and among its members were Prof. G. Srinivasan, Prof. S. Ananthkrishnan, Prof. S. N. Tandon, ASTROSAT Project Director and others. The APMC played a very constructive role in the successful development of the ASTROSAT instruments and I acknowledge it. I wish to especially thank Dr. George Joseph and Prof. G. Srinivasan for their steadfast support and advice at all stages of ASTROSAT. A large measure of credit for the success of ASTROSAT mission is due to very able leadership of the project by Mr. V. Koteswara Rao who led the project as its Project Director during 2003–2009 and by Mr. K. S. Sarma who was the Project Director during 2009–2015. I gratefully acknowledge them and their teams for the realization of ASTROSAT. Dr. K. Rangan got the ASTROSAT mission approved during his tenure and provided strong support for it. His successors continued to support the ASTROSAT and I am grateful to all of them. Dr. P. S. Goel was the Director of ISAC when ASTROSAT was approved. He and his successors provided valuable guidance and advice for the ASTROSAT and I am thankful to them.

My first visit outside India was to Nagoya University. I had fond memories of working in the group of Prof. S. Hayakawa, a renowned cosmic ray physicist who was a very thoughtful and kind-hearted person who took a lot of care to ensure my wellbeing at Nagoya. During this visit, I had fruitful interactions with Prof. Y. Tanaka and Prof. F. Makino and learnt a lot from them about space instrumentation. In the collaborative experiments for simultaneous observations of Sco X-1 in X-ray and optical bands, I had the pleasure of collaborating with Prof. M. Matsuoka, a gentle and soft spoken person who invited me to RIKEN in 1997 as a Visiting Professor. I also recall happy interactions and friendship of Prof. K. Yamashita.

My 3 year stint at Caltech as a Research Fellow with Prof. Gordon Garmire on the HEAO A-2 experiment was a memorable experience of my career. I am thankful to Gordon for his generosity, reposing confidence in me and entrusting me with the A-2 development work. I developed close collaboration and friendship with Guenter Riegler during development of the A-2 experiment and later when I visited JPL for one and a half year to do science analysis of LED data. It was a very fruitful collaboration which extended till almost 1986. I thank Guenter for his warm and friendly treatment. In 1987–1988, I visited the X-ray Astronomy Group of Martin Weisskopf at MSFC as a senior RRA and had a very fruitful collaboration with Brian Ramsey, an outstanding experimenter. Working with Brian was an enjoyable experience and I cherish it. My daughter Rashmi Bansal, an author of several books, carefully and patiently went through this article, and corrected and edited it to make it readable. I gratefully acknowledge her contribution. I dedicate this memoir of my scientific journey to my wife Rama with whom I will be celebrating 50 years of our union in November 2019. Her steadfast support and loving companionship have been a great source of inspiration to me through the ups and downs of life. She has been a pillar of strength by my side and whatever little that I could do in this journey was due to her unflinching faith in me. I am deeply indebted to her for being such a wonderful life partner. I thank Prof. Ip Wing-Huen for inviting me to write this memoir of my scientific journey.

References

Agrawal, P. C., Damle, S. V., Gokhale, G. S., et al. 1965a, Proc. Ninth Intern. Conf. on Cosmic Rays, London, 1, 453
Agrawal, P. C., Damle, S. V., Gokhale, G. S., et al. 1965b, Proc. Ninth Intern. Conf. on Cosmic Rays, London, 1, 457
Agrawal, P. C., & Kunte, P. K. 1968, Nuclear Instruments and Methods, 63, 258
Agrawal, P. C., Biswas, S., Gokhale, G. S., et al. 1969, Nature, 224, 51
Agrawal, P. C., Iyengar, V. S., Kalgaonkar, M. A., et al. 1971, Nuclear Instruments and Methods, 95, 29
Agrawal, P. C., Gokhale, G. S., Iyengar, V. S., et al. 1971, Nature, 232, 38
Agrawal, P. C., Garmire, G. P., Riegler, G. R., et al. 1976, SPIE, 93, 113
Agrawal, P. C., & Riegler, G. R. 1979, ApJ, 231, L25
Agrawal, P. C., & Riegler, G. R. 1980, ApJ, 237, L33
Agrawal, P. C., Riegler, G. R., & Rao, A. R. 1983, Nature, 301, 318
Agrawal, P. C., Rao, A. R., & Sreekantan, B. V. 1986, MNRAS, 219, 225
Agrawal, P. C., Ramsey, B. D., & Weisskopff, M. 1989, Nucl. Inst. and Meth., 277, 557
Agrawal, P. C. 2006, Adv. Space. Res., 38, 2989
Agrawal, P. C. 2016, Physics News, 46, 11
Agrawal, P. C. 2017, J. Astrophsics & Astronomy, 38, 27
Chitnis, V. R., Rao, A. R., & Agrawal, P. C. 1998, A&A, 331, 251
Chitnis, V., Rao, A. R., Agrawal, P. C., et al. 1993, A&A, 268, 609
Danjo, A., Hayakawa, S., Ikeda, M., et al. 1971, Space Research (Akademis - Verlag, Berlin), XI, 1373
Giacconi, R., Gursky, H., Paolini, F., et al. 1962, Phys. Rev. Lett., 9, 439
Long, K. L., Agrawal, P. C., & Garmire, G. P. 1975, ApJ, 197, L57
Manchanda, R. K., Iyengar, V. S., Agrawal, P. C., et al. 1971, Nature Physical Science, 232, 190
Matsuoka, M., Fujii, M., Miyamoto, S., et al. 1972, Nature Physical Science, 236, 53
Paul, B., Agrawal, P. C., Rao, A. R., et al. 1998, ApJ, 492, L63
Ramsey, B. D., & Agrawal, P. C. 1989, Nuclear Instruments and Methods, 278, 576
Rao, A. R., Agrawal, P. C., Manchanda, R. K., et al. 1986, Adv. Space Research, 7, 129
Riegler, G. R., Agrawal, P. C., & Mushotzky, R. F. 1979, ApJ, 233, L47
Rothschild, R., Boldt, E., Holt, S., et al. 1979, Space Science Instrumentation, 4, 269
Roy, J., Agrawal, P. C., Dedhia, D. K., et al. 2016, Experimental Astronomy, 42, 249
Singh, K. P., Agrawal, P. C., Manchanda, Naranan, S, and Sreekantan, B. V. 1983, A&A, 117, 319
Singh, K. P., Tandon, S. N., Agrawal, P. C., et al. 2014, in Proc. SPIE , Space Telescopes and Instrumentation 2014: Ultraviolet to Gamma Ray, 9144, 91441S (July 29, 2014); doi:10.1117/12.2062667
Singh, N. S., Naik, S., Paul, B., et al. 2002, A&A, 392, 161
Yadav, J. S., Rao, A. R., Agrawal, P. C., et al. 1999, ApJ, 517, 935