B. V. Sreekantan: A versatile and humane scientist

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'*It is the duty of people like us to stay in our own country and build up outstanding schools of research such as some other countries are fortunate to possess*.'

That was the vision of Homi Bhabha, the founder director of Tata Institute of Fundamental Research (TIFR). Set up on 1 June 1945 by Bhabha with the support of Sir Dorabji Tata Trust, TIFR's mission was to undertake front-ranking research in basic sciences in India.

TIFR began functioning on the campus of Indian Institute of Science (IISc) at Bengaluru but it moved to Mumbai in October 1945. The first makeshift laboratories were in a bungalow on Peddar Road named 'Kenilworth', owned by Bhabha's aunt. As the research activities grew, it shifted to the Royal Yacht Club building near Gate Way of India in September 1949 and finally moved to its present campus at Colaba in 1961.

On 6 August 1948 a young man who had just obtained his M Sc in Physics from Mysore University, walked into the premises of Kenilworth. He was applying for Research Studentship. In answer to the query about his area of interest the young man had filled 'Theoretical/Experimental Physics'.

He was ushered into a room where he was first examined for his knowledge of physics by a committee chaired by Bhabha. He was then asked to appear before a second committee that consisted of Bhabha, D. D. Kosambi and Levy. 'The candidate has already been examined in physics,' said Bhabha to his colleagues. 'We must now test his knowledge in mathematics.' Levy then put some questions on matrices while Kosambi asked some questions in statistics. After the interview, the candidate was again called to Bhabha's room.

'Sreekantan, we have decided to admit you. Tell us whether you want to do theory or experimental research'. Sreekantan replied, 'Sir, you have interviewed me. I go by your advice'. Bhabha said, 'Young man, if you join the experimental group then perhaps you may also be able to do theoretical work. The other way is doubtful. Moreover, you have some experience in electronics which very few have in this country. If I were you, I will choose to do experimental work.'[1]

Sreekantan decided to follow Bhabha's advice and joined the Cosmic Ray group of TIFR on 12 August 1948. Thus began his long and eventful journey in the world of science.

Early life, education and research areas

Badanaval Venkatasubba Sreekantan was born on 30 June 1925 to B. V. Pandit and Laxmi Devi in a town known as Nanjangud in the former Mysore state, in a family of temple priests. His ancestors originally hailed from Telugu speaking Andhra region but migrated to Karnataka almost 200 years before. It was a big family with 8 brothers and 3 sisters, Sreekantan being the fifth brother.

The family had a scholarly tradition and there was an intellectually stimulating atmosphere at home. There was a huge collection of books on a variety of subjects covering liberal arts, literature, philosophy, mythology, science as well as fiction and thrillers. Sreekantan read extensively from this collection and acquired broad exposure to the world of knowledge.

His father departed from the family tradition of priesthood and got admitted to an Ayurvedic Medical College in Mysore. After completing his degree B. V. Pandit became an Ayurvedic doctor or 'Vaidya' as they were called. Apart from Ayurveda, he was also proficient in Sanskrit and Vedas. Later he developed and started selling dental powder which became very popular and came to be known as 'Nanjangud' dental powder. He also made *Kasturi* pills for stomach ailments and various other Ayurvedic preparations. The business flourished and products of Nanjangud factory became widely known, especially in south India. Even today it is still doing brisk business and Sreekantan is associated with the company as the Chairman of its Management Board.

Sreekantan completed high school in Nanjangud and moved to Mysore for a 2-year Intermediate degree. Science subjects were taught to him by some very dedicated teachers. This was instrumental in the young mind developing a deep interest in science. He was awarded B Sc (Hons) in Physics (1946) and M Sc in Physics (1947) with specialization in Wireless, both by Mysore University. Initially Sreekantan joined IISc (Bengaluru) as a Research Scholar in the Department of Communication but in 1948 moved to TIFR (Mumbai) when Bhabha selected him for research in experimental cosmic ray physics.

Sreekantan had a remarkably successful career at TIFR culminating in his elevation as its Director in January 1975. He demitted office in 1987 on reaching superannuation and left behind a rich legacy in cosmic ray physics and astrophysics. With strong support from Bhabha and MGK Menon, he nurtured and built an internationally recognized research group which studied the characteristics of high energy cosmic rays using a variety of detectors at ground level, mountain altitude as well as in deep underground mines. Even today the High Energy Cosmic Ray group at TIFR is quite active, carrying out studies of cosmic rays with an Extensive Air Shower (EAS) array at Ooty. This array employs hundreds of scintillation and proportional counters and associated complex electronics.

His early experiments in deep Kolar Gold Field (KGF) mines ultimately led to studies of energetic muons at a depth of up to 2760 m. Failure to detect any cosmic ray produced muons at 2760 m depth immediately suggested the possibility of detecting interactions of neutrinos in deep rocks in the mines. In fact, the first detection of a cosmic ray produced neutrino event was reported from KGF experiment. This paved the way for the TIFR group undertaking the well-known experiment to search for Proton Decay in the decade 1980–90 in the KGF mines.

In the late sixties, after he returned from MIT, Sreekantan recognized the importance of the emerging field of X-ray astronomy for probing high energy processes in the universe. He started balloon-borne experiments to study cosmic X-ray sources above 20 keV and built a strong group which in due course developed expertise in fabrication of highly sophisticated X-ray detectors for space-borne X-ray astronomy missions.

The ambitious Multiwavelength Astronomy Observatory (Astrosat) is led by TIFR which is also responsible for the design and development of three of the X-ray instruments, a culmination of the research programme seeded by Sreekantan. The Astrosat Observatory weighing 1.6 tonne will have four X-ray astronomy instruments and an ultraviolet instrument. It is likely to be launched in mid-2015 by PSLV and will be a fitting tribute to Sreekantan on his 90th birthday.

It may be pointed out that Sreekantan is probably the only scientist who had the unique distinction of performing experiments from the deepest depth of a mine on problems related to cosmic ray muons, neutrinos and proton decay to altitudes of up to several hundred kilometres with balloon and rocket-borne detectors to probe mysteries of X-ray emission from neutron stars and black holes. His research spanned studies of particles with energies of MeV to PeV and photons of keV to tens of TeV. Thus his research activities span a broad canvas in cosmic ray physics and astrophysics.

Early research and experiments on μ-mesons, neutrino detection and proton decay experiments

Soon after Sreekantan joined TIFR, Bhabha suggested that he should set up an experiment to study decay of μ-meson (now commonly known as Muons) and its decay spectrum by studying the literature and present a colloquium. It actually stretched to three colloquia due to numerous questions and suggestions on improving the experiment by Bhabha and Kosambi. Sreekantan was now clear about all aspects of the experiment that kept him occupied for the next two years. Muon life-time was already known to be about two microseconds. Bhabha wanted him to study its decay spectrum and measure the life-time. This required building of pulse electronics, triggered cathode ray tube, coincidence circuits, etc. with better than microsecond capability.

The Second World War had just ended. A huge quantity of electronic units used in signalling and communication in the war had become surplus and a lot of these found their way to Chor Bazar (a kind of flea market in Mumbai). TIFR bought a lot of this equipment at throwaway prices and salvaged various components for use in experiments that were being set up. Vacuum valves and oscilloscope parts came in especially handy for Sreekantan to fabricate electronics for his experiment.

Geiger Muller (GM) counters filled with argon and distilled alcohol/ether as quench gas were already being made by H. L. N. Murthy, an expert in glass work whom Bhabha had hired in Bengaluru. A magnet with about 5000 gauss field was used to separate positive μ-mesons. The experiment was performed during 1948–51 and Sreekantan derived the life-time of positive muons to be 2.24 ± 0.15 microsecond. Bhabha wanted quick publication of results in an Indian journal and so it was published in *Proceedings of Indian Academy of Sciences*.

A little later Bhabha suggested study of angular distribution of muons by studying their flux underground at KGF mines situated at 870 m above sea level. He wanted to explore if the particles deep underground were only μ-mesons or also some other types of particles. The KGF mines were then owned by an English Company (John Taylor & Sons) and it had excellent infrastructure. Power was available at different depths in the mines and the shafts had lifts capable of transporting big and heavy equipment deep underground. There existed an extensive network of tunnels at different depths in which experiments could be set up. And a guest house facility as well. The company readily agreed to support TIFR experiments and provided all facilities free of cost. The only problem was that power supply in the mines was 25 cycles AC supply; so transformers had to be made for converting it to 50 cycles supply (on which all the equipment used in the experiments worked).

Sreekantan set up the experiment with the assistance of S. Naranan and P. V. Ramanamurthy who joined the group soon after. It took 18 months to set up the experiment and by October 1951, it started taking the data. Measurements of intensity of particles at different depths using GM counter trays operating in coincidence were carried out. Vertical intensity was measured by vertical axis counter telescope and angular distribution was measured by tilting the counter telescope axis at different angles from the vertical. Sreekantan noted that as they went deeper, the intensity of particles triggering coincidence reduced drastically but count rates of individual GM counters became very high. This was puzzling. He reported this to Bhabha who immediately suggested that this must be due to high radioactivity in the underground rocks. 'Check if the count rates are reduced by putting lead absorbers', said Bhabha. This was indeed found to be the case and the radioactivity was attributed to gamma rays produced by radioactive decay of Thorium^{232} in the rock.

The intensity of muons and their angular distribution were measured at different depths. The measurements covered from surface to a depth of up to 1008 mwe (meter water equivalent). It implied energy of muons from 3 GeV to 370 GeV, the minimum energy required to penetrate to a depth of 1008 mwe. It was noted that the intensity dropped sharply from 9400 counts/hour at 10 mwe to 25.6 counts/hour at 503 mwe and reduced further to 2.33 count/hour at 1008 mwe. The energy spectrum of muons was measured from the depth-intensity curves and this was used to deduce the energy spectrum of the parent π-mesons. Angular distribution of μ-mesons ranged from $\cos^3 \theta$ at shallower depths to $\cos^4 \theta$ at greater depths.

Sreekantan finished these experiments by 1953 and submitted Ph D thesis to Mumbai University on the intensity and angular distribution of muons at different depths in KGF mines. Bhabha was his guide and the renowned cosmic ray physicist Bruno Rossi of MIT was the external examiner.

From the depth-intensity measurements it became immediately obvious that probing intensity at greater depths in the mines required a counter telescope of much larger area. By then V. S. Narasimham had joined the group in 1959 and a Japanese cosmic ray researcher S. Miyake (Osaka City University) also evinced keen interest in the experiment.

Ramanamurthy, Narasimham and Miyake set up a counter telescope of two scintillation counters, with a GM counter and lead absorber in between, having 3 sq. m. area to measure the intensity of particles at various depths up to about 3 km, the deepest accessible level. The measurements were carried out at 5 different depths from 270 m (810 mwe) to 2760 m (8400 mwe). As expected, the intensity declined rapidly with increasing depth. At 800 m 1029 coincidence counts were recorded in 100 hours, declined to 127 counts in 944 hours and further reduced to 18 counts in 3000 hours at deeper levels. At the deepest level of 2760 m, no particle was detected in 2880 hours implying a limit of $\leq 3.5 \times 10^{-3}$ count per hour. Thus at a depth of 2.76 km there was virtually no background of charged particle.

'This will be an ideal place to study cosmic ray produced very weakly interacting neutrinos!' so thought Menon, Narasimham, Miyake, Ramanamurthy and Sreekantan. It was however realized that detection of cosmic ray-produced vertically moving neutrinos will require a detector with several kilotonnes of material which was impractical. Neutrinos have extremely tiny interaction cross-section and they can virtually travel through the whole earth. Neutrinos travelling horizontally or coming from opposite side of the earth may interact in the mass of the rocks in the mines producing muons that can be detected. Such neutrino-produced muon events will appear at large zenith angles and as horizontal events.

An experiment for studying neutrinos was planned jointly by TIFR with Durham University (UK) and Osaka City University (Japan). Neutrino detectors were designed by vertically stacking scintillation counters operating in coincidence. Neon Flash Tubes (NFTs) as track detector and either lead or iron absorbers were sandwiched between the scintillation counters. The experiment was set up at a depth of 2.3 km and became operational in April 1965. The experiment ran for several years and 18 events were recorded that could be clearly attributed to neutrino interactions in the rock. Much larger number of neutrino events (≈ 300) were later detected in the proton decay experiments conducted during 1980–90.

In the seventies, some models of Grand Unification Theory (GUT) had predicted non-conservation of baryons implying decay of protons with life time in the 10^{31}–10^{34} range. Menon, Miyake, Narasimham and Sreekantan thought that this should be experimentally detectable in the low background environment of deep KGF mines. Motivated by this, TIFR and the City University of Osaka planned a joint Proton Decay experiment in KGF. Narasimham, M. R. Krishnaswamy and N. K. Mondal, who joined the group in 1977, along with the Japanese scientists from Miyake's group, played the lead role in setting up these experiments.

Phase l of the experiment with sensitive area of 4 m × 6 m was set up at a depth of 2.3 km by using 1600 hundred proportional counters (PCs) arranged in 34 alternately orthogonal layers with 140 tonnes of steel plates sandwiched between the counter layers. Proton decay events will manifest as tracks of events fully confined in the detector volume. This experiment ran for almost 8 years. A much larger volume detector with area of 6 m × 6 m employing 4000 PCs in 60 layers interspersed with steel plates of 340 tonne mass was set up at 2 km depth as Phase ll of the experiment which ran for 5.5 years and recorded large number of neutrino-produced muons. Several candidate events that could not be explained by any known process or decay modes were listed.

If these are assumed to be due to decay of protons, the life-time of proton was estimated to be 1.4×10^{31} years. Several experiments with fine grain detectors as well as Water Cerenkov detectors of much larger volume and mass were carried out by other laboratories in deep mines to detect decay of protons but no unambiguous event that can be attributed to proton decay was found. Based on these a lower limit to proton life time was placed as $>10^{33}$ years.

Sreekantan with wife Ratna at a conference in TIFR in early eighties (courtesy: BVS photo album).

Studies of high energy cosmic rays at Ootacmund and KGF

Sreekantan submitted his Ph D thesis and proceeded to USA in 1954 to work at MIT with Bruno Rossi, a well-known figure in cosmic ray research. Before going to USA he got married to Ratna, a proficient singer in Carnatic vocal music, who hailed from Bengaluru.

Enroute USA he visited several cosmic ray laboratories in France and UK to familiarize with their research and learn about the latest developments in high energy physics. At MIT he analysed a number of cloud chamber pictures to understand production of K-mesons, their decay products and their properties. He also spent a few months at the accelerator facility at Brookhaven National Laboratory and analysed data obtained with a big cloud chamber experiment set up by the MIT group. A series of three papers giving results of K-meson decay products came out in collaboration with H. S. Bridge and others of MIT.

A few years after Sreekantan's studies of muons at KGF, Bhabha asked him to fabricate a Cloud Chamber so that studies of new particles produced in cosmic ray interactions can be investigated with it. A small cloud chamber was already fabricated at IISc by two young researchers who worked in the laboratory of P. M. S. Blackett at Manchester University. After Bhabha moved to TIFR, the cloud chamber was shifted to Mumbai by A. B. Sahiar who was familiar with the operation of cloud chamber.

Before Sreekantan left for USA, Bhabha and he visited Ooty to select a site for a cosmic ray laboratory for studying interactions of cosmic rays. By December 1954 two new cloud chambers named as Rani and Maharani were built and installed in the cosmic ray laboratory at Ooty by Sahiar, Naranan, Ramanamurthy and A. Subramanian to study the production of so-called V-particles which was then a hot topic.

This was followed by the design and fabrication of world's largest multiplate cloud chamber of ($2 \text{ m} \times 1.5 \text{ m} \times 1 \text{ m}$ size) that had 21 iron plates of 2.5 cm thickness for studying interactions of hadrons. This giant cloud chamber was developed in India with the involvement of Miyake and his group. An air shower array was also set up at Ooty to study Extensive Air Showers (EAS) produced by interactions of very high energy cosmic rays in the atmosphere. The cloud chamber was operated with the EAS array to study cores of EAS and deduce characteristics of high energy interactions. This study led to several new and interesting results on high energy interactions of protons.

Sreekantan, Subramanian and Ramanamurthy also designed a Total Absorption Spectrometer (TAS) along with an Air Cerenkov Counter to distinguish between interactions of protons and pions with the iron nuclei in 10–40 GeV range. The big cloud chamber was operated in coincidence with the Cerenkov detector and total absorption spectrometer. The triple detector system was operated for many years to study time structure of nuclear component in the cores of EAS. Based on study of arrival time distribution of low energy hadrons in the cores of EAS of 10^{14}–10^{16} eV, S. C. Tonwar and Sreekantan came to the conclusion that their results could be explained only if the baryon production cross-section increased with energy. The result was independent of the composition of primary cosmic rays. This important finding that nucleon-anti nucleon production cross-section increases significantly with energy was subsequently confirmed by experiments with 30 GeV proton beam at the CERN accelerator.

Using the same detector set up and EAS array, R. H. Vatcha and Sreekantan measured charged to neutral (C/N) ratio for high energy hadrons in showers of 10^{14}–10^{16} eV energy range and comparing these results with those from Monte Carlo simulations they came to the conclusion that copious production of baryons in high energy interactions is inevitable. This result as well as the one obtained by Tonwar and Sreekantan confirmed the important role of baryon production in very high energy interactions and showed that about 20–25% of particles produced in hadron-air nucleus collisions at 10^{15} eV are baryons.

The Ooty air shower array consisted of large number of scintillation detectors, neutron monitor type hadron detectors and muon detectors, with fast timing capability, to measure the shower size, their core location, arrival directions of showers and energy of GeV range muons. The EAS group at Ooty included B. K. Chatterjee, G. T. Murthy, M. V. S. Rao, K. Sivaprasad and Sreekantan who carried out detailed studies of the various characteristics of showers in 10^{14}–10^{16} eV range for more than a decade. The main objective was to measure the energy spectrum of primary cosmic rays and infer their composition and energy dependence from the measured shower characteristics.

In parallel an EAS array of scintillation counters was set up in 1965 at surface at KGF to measure shower size. Simultaneously very high energy muons associated with showers with energy >220 GeV and >640 GeV were detected with scintillation detectors at a depth of 270 m and Water Cerenkov detectors at 600 m depth respectively. The EAS group at KGF included B. S. Acharya, Srinivasa Rao, Sivaprasad, Naranan and Sreekantan and later P. R. Vishwanath. Variations of number of very high energy muons (exceeding the above thresholds) were studied as a function of shower size and the measurements compared with those obtained from Monte Carlo simulations based on models of primary composition. The results were best explained by a model of primary composition in which heavy nuclei disappear at 8×10^{13} eV due to photo-disintegration but protons of galactic origin are present up to $\sim 7 \times 10^{15}$ eV. Above this energy the proton spectrum steepens gradually due to their leakage from the galaxy and it is dominated by protons of extragalactic origin.

The work at KGF was discontinued in early nineties following the closure of the KGF mines. However the vastly expanded EAS array at Ooty that includes several hundred scintillation counters and very large number of proportional counters is still being run by S. K. Gupta and his team along with the Osaka City University Group to study characteristics of very high energy cosmic rays.

Sreekantan in discussion with famous Cosmic Ray trio of Lal (D. Lal), Pal (Yash Pal) and Peters (B. Peters) in late fifties at TIFR (courtesy: BVS Photo Album).

Sreekantan's contribution in early phase of X-ray astronomy at MIT

The period 1960 to 1990 was a golden age of astronomy. Path-breaking discoveries were made and new windows opened up to probe the mysteries of the universe. A new generation of sensitive electromagnetic and particle detectors brought electrifying new data. The advent of the Space Age and the 'Moon Mission' also gave a tremendous boost to astrophysics.

In 1962, Bruno Rossi and his group at MIT and Ricardo Giacconi and his group working at a company called American Science and Engineering, jointly carried out a rocket experiment in USA with the ostensible aim of detecting X-rays from the Moon. Rossi and Giacconi had a strong hunch that there ought to be X-ray bright stars in the nearby universe. They used simple pan cake-shaped Geiger Muller counters having mica windows in the experiment. When the detectors looked at the Moon no detectable emission was registered. However while scanning a region in the vicinity of the galactic centre in the southern sky, they recorded intense X-ray emission. Detailed analysis revealed that the source of X-rays was beyond the solar system and located in the Scorpious constellation and named as Sco X-1. Thus X-ray astronomy was born in 1962 with the serendipitous discovery of Sco X-1.

In the following four decades it grew rapidly with launch of a series of X-ray satellites of vastly improved sensitivity that led to detection of almost all classes of celestial objects as X-ray sources. For this momentous discovery Giacconi was awarded the Nobel Prize in 2002 that marked the 40th anniversary of this discovery.

The discovery of Sco X-1 greatly puzzled astrophysicists. Its estimated distance of a few hundred parsecs and its observed X-ray intensity implied an X-ray luminosity of at least 10^{35} ergs/sec. There was no known process that could produce such high X-ray luminosity in a star. The nature of Sco X-1 and the process that produced such intense X-rays from it remained elusive. Was it a point like stellar object or an extended source possibly a supernova remnant (SNR)?

The MIT–AS&E collaboration decided to measure the size of the source and its precise location to be able to investigate if it has any optical counterpart. At this crucial juncture, in 1965, Sreekantan joined the MIT group that included Hale Bradt and Gordon Garmire, and got involved in the rocket- borne X-ray astronomy experiments.

At that time a Japanese cosmic ray physicist Minoru Oda was also visiting MIT and he came up with the brilliant idea of using proportional counter equipped with a new type of collimator that came to be known as modulation collimator for precise measurement of the location and size of the source. Sreekantan and Oda were part of the MIT–AS&E team that carried out rocket observations of Sco X-1 in 1965 with modulation collimator. The experimental data showed that the size of Sco X-1 was <20 arcsec and it was most likely a stellar source and not a SNR. From the same experiment they also derived a precise measurement of the position of Sco X-1 to an accuracy of about 10 arcsec. A blue star-like object of about 13th magnitude was found in the error circle of the X-ray source.

At a function in TIFR to commemorate the Legacy of Bhabha: Left to Right M. G. K. Menon (Member Planning Commission), J. R. D. Tata (Chairman Governing Council of TIFR); B. V. Sreekantan (Director TIFR) and R. Ramanna (Chairman Atomic Energy Commission) (courtesy: TIFR Archives).

Optical studies of the star with the involvement of astronomers at Palomar and Tokyo indicated that it was an old nova-like star. This implied that Sco X-1 is truly an X-ray star whose X-ray luminosity is about 1000 times its optical luminosity. It remained a mystery till the discovery of X-ray binary sources Cen X-3 and Her X-1 which were found to be pulsating in X-rays from UHURU satellite in 1971. Soon it was realized that matter accreting onto a compact object like a neutron star or a black hole under its strong gravity can attain temperatures as high as 10^8 or even higher and it copiously radiates X-rays.

Sreekantan and X-ray Astronomy at TIFR

Sreekantan returned from MIT in 1967 and looked forward to initiating X-ray astronomy research at TIFR. After the discovery of Sco X-1 many bright cosmic sources like Crab Nebula (a known SNR), Cyg X-1, etc. were discovered in quick succession from rocket experiments. In July 1964 George Clark of MIT (he was also a cosmic ray physicist) carried out a balloon experiment from Palestine, Texas with a scintillation counter and detected X-rays in 15–60 keV band from Crab Nebula. Independently, K. McCracken had carried out two balloon experiments from Hyderabad in April 1965 and reported detection of 20–58 keV X-rays from Cyg X-1 from both experiments. This strongly suggested that X-ray emission of cosmic sources extends to at least 60 keV and higher.

At TIFR, Sreekantan in 1967 realized the potential of balloon-borne hard X-ray astronomy experiments in understanding the nature of X-ray sources and their X-ray emission processes. He noted that TIFR had the required infrastructure like balloon fabrication and launch facility as well as young persons familiar with the use of a variety of radiation detectors like scintillation detectors and development of electronics for balloon instruments. This made it possible to embark into this new area of research.

It was also realized that cosmic ray produced background over Hyderabad will be minimal due to its low latitude (17°N). At that time this writer (PCA) was working on a balloon experiment to study heavier nuclei in cosmic rays using Scintillation–Cerenkov–Spark Chamber telescope and he jumped at this exciting opportunity to work in a new virgin field of research. Ravi Manchanda who had joined TIFR in 1966 and P. K. Kunte who had developed orientation systems for pointing in space, also joined the new group followed by V. S. Iyengar from PRL. Sreekantan received strong support in initiating this new research programme from the then Director M. G. K. Menon by providing funds for importing two US made balloons for launches in the night. At that time, TIFR fabricated balloons only for day-time launches.

An X-ray instrument using a 3 mm thick sodium iodide detector (100 cm^2 area) surrounded by a plastic scintillation veto detector with associated signal processing and data recording electronics and orientation capability was developed in about a year, and made ready for studies of Sco X-1 in balloon experiment in April 1968. The first successful balloon-borne experiment was conducted in April 1968 followed by another in December 1968. X-rays of >20 keV were clearly detected from Sco X-1. It was exciting to find that during the flight of 22 December 1968, the intensity of Sco X-1 varied in the course of about 90 minutes confirming an earlier report of variability by the MIT group. These results were published in *Nature*. Another important finding from these experiments was the detection of hard component of Sco X-1, probably of non-thermal origin, up to at least 100 keV, a result that is still being quoted after 45 years.

Sreekantan at the TIFR Balloon Facility Launch ground in Hyderabad instructing Balloon Control and Data Receiving room to be ready for launch of balloon experiment for X-ray Astronomy observations (courtesy: Balloon Facility).

On 6 April 1971 another experiment was conducted to study X-rays from Cyg X-1 which is the brightest cosmic source above 20 keV. Cyg X-1 was a hot topic of discussion in those days as it was optically identified with a 5.6 day binary. Based on the mass estimates of the optical companion as well as the binary parameters it emerged as a first credible candidate for a black hole of ≥7 solar mass. The TIFR experiment indicated rapid variability of Cyg X-1 intensity over a period of several minutes and also discovered occurrence of an X-ray flare. These results appeared in a series of three papers in *Nature* and brought Sreekantan and his group instant international recognition. As a result this author received offer of post-doctoral position of Research Fellow from Gordon Garmire of Caltech (close collaborator of Sreekantan at MIT) as soon as he submitted his Ph D thesis.

Buoyed by this early success Sreekanatan and his group continued balloon experiments vigorously till mid-seventies and studied several newly discovered X-ray sources like Her X-1, Aql X-1, etc. After the trailblazing success of the first X-ray satellite UHURU, a series of X-ray satellites were launched by NASA, ESA, Japan, etc. in the seventies and eighties, resulting in an explosive growth of X-ray astronomy. As a result, rocket and balloon experiments declined rapidly as the observing time in these experiments was limited. Sreekantan and his group missed this exciting phase of X-ray astronomy because until the success of PSLV (Polar Satellite Launch Vehicle) in 1993, India had limited capability of launching satellites of 120–150 kg mass with science instruments of up to about 20 kg. Hence Indian X-ray astronomers continued work albeit with reduced vigour, on development of new detectors for space missions, awaiting opportunities for experiments on Indian satellites.

In November 1968, U. R. Rao (PRL, Ahmedabad) had carried out two rocket experiments from Thumba Equatorial Rocket Launching Station (TERLS) located at a latitude of 8°N for studying Sco X-1 and other newly discovered X-ray sources. Sreekantan with S. Naranan and V. S. Iyengar also embarked on rocket experiments in early seventies to study low-energy end of X-ray spectra of bright X-ray stars. Several experiments were conducted using Indian made Centaur rockets to study Sco X-1, Crab Nebula, etc. Another initiative was the development of thin window proportional counters for investigating soft X-ray sky in 0.1–3 keV range.

This author had just returned from Caltech after his deep involvement in the development of soft X-ray detectors of A2 experiment, a joint project of NASA/GSFC and Caltech, launched aboard High Energy Astronomy Observatory-1 (HEAO-1) in 1976. This experience proved valuable in development of soft X-ray detectors similar to those of A2 experiment, with the involvement of KP Singh who had joined the group as a research scholar in 1973. A rocket flight was carried out in 1979 with RH-560 rocket to map the diffuse cosmic X-ray background in 0.1–0.18 keV, 0.1–0.28 keV and 0.5–3 keV bands. Intensity and spectral maps of diffuse soft X-ray sky were constructed from this experiment and constituted the Ph D thesis of K. P. Singh. Sreekantan participated in different phases of the rocket experiments and encouraged the group to find solutions to the technical difficulties that cropped up at various stages.

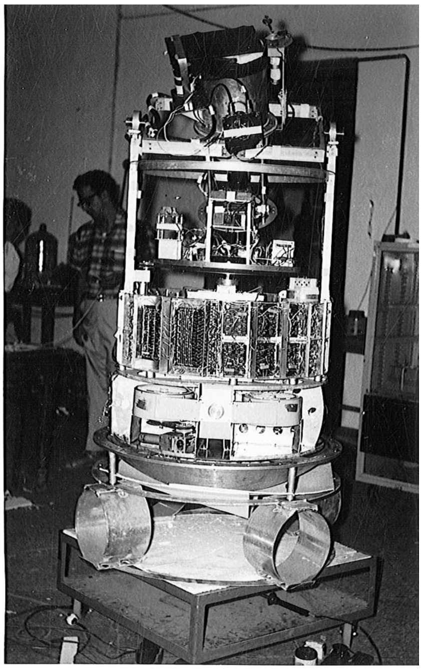
After one more rocket-borne experiment this activity was discontinued as satellite-borne experiments provided much better sensitivity.

Sreekantan's collaboration in X-ray astronomy with Japanese groups

The MIT-ASE experiment that discovered Sco X-1 also found that there was a Diffuse Cosmic X-ray Background (DCXRB) and its spectrum at low energy was measured in several rocket experiments. The spectrum was relatively unexplored above 20 keV. S. Hayakawa, a well-known Japanese astrophysicist at Nagoya University, and M. Oda of Tokyo University (later moved to Institute of Space and Astronautical Science known as ISAS) are regarded as pioneers of X-ray astronomy research in Japan. Hayakawa set up an experimental X-ray astronomy group at Nagoya University which included Y. Tanaka, and young researchers M. Matsuoka, K. Yamashita and F. Makino, all of whom later made notable contributions and rose to be leaders of X-ray research groups in Japan.

Hayakawa considered measuring the energy spectrum of DCXRB in hard X-ray, low-energy gamma-ray region in a balloon experiment from Hyderabad. He discussed this idea with Sreekantan and planned a collaborative balloon experiment. An instrument was designed and fabricated at Nagoya University by Tanaka and Makino and this author was deputed there to work on this instrument. A novel feature of this experiment was measurement of non-cosmic X-ray background using a movable thick caesium iodide detector that periodically blocked the opening aperture through which X-rays entered. A balloon flight with this instrument was carried out from Hyderabad on 8 May 1971 and a second experiment was performed in 1974. Data from these experiments were used to measure the spectrum of diffuse cosmic X-ray and low energy gamma-ray background in ~100 keV to 4 MeV region. The results indicated that the background spectrum above 100 keV steepens and then flattens above 500 keV.

X-ray luminosity of Sco X-1 being about 1000 times the optical luminosity, the optical brightness of the companion star will be affected profoundly by X-rays impinging on its surface leading



Hard X-ray Astronomy Instrument used in Balloon Experiments during 1971–74 for studies of Binary X-ray stars.

to correlated optical and X-ray flux variations. This hypothesis needs to be checked by making simultaneous X-ray and optical observations of Sco X-1. Oda and Hayakawa jointly proposed to Sreekantan X-ray observations of Sco X-1 from balloon experiments to be conducted from Hyderabad, and simultaneous optical observations from Rangapur and Tokyo observatories.

The X-ray instrument was jointly developed by ISAS-Nagoya group and flown on a balloon on 1 May 1971. Sreekantan arranged for optical observations with a 48 inch telescope of Japal-Rangapur observatory operated by Osmania University but due to tracking difficulty observations could not be made. Fortunately an old 8-inch size refractor telescope at Nizamiah observatory in Hyderabad could be used to make photographic observations of Sco X-1. A Ham operator was located in Hyderabad and his services were used to communicate with the astronomer at Tokyo in real time for simultaneous observations from Okayama observatory.

Two more balloon experiments were conducted on 16 and 19 April 1972 for simultaneous X-ray and optical studies of Sco X-1. This time the photoelectric optical observations were obtained with the 48 inch telescope and photographic measurements were made with the 8 inch astrograph and a 12 inch reflector set up at Hyderabad. From these experiments it was convincingly established that there was a positive correlation between X-ray flux and optical brightness. Sreekantan played an important role in the success of this campaign by organizing the required logistics and support. The results obtained from the experiments appeared in a series of three papers, two of them in *Nature*.

Sreekantan's last collaboration experiment with the ISAS-Nagoya group was in 1975 during the Lunar Occultation of Crab Nebula. X-rays in the Crab Nebula are thought to be produced by synchrotron emission of energetic electrons which implies that the size of the X-ray emitting region of the pulsar nebula at higher energy should be smaller compared to that at lower energy. Lunar occultation of Crab presented an excellent opportunity to test the synchrotron origin hypothesis. Two large area scintillation detector instruments were developed and two balloon flights launched to coincide with the occultation of the Crab Nebula on 24 January 1975. Results indeed showed the size to be smaller in hard X-rays compared to that measured at lower energy consistent with the synchrotron origin of X-rays.

Sreekantan's role in TeV gamma-ray astronomy at TIFR

In early fifties, Crab Nebula was recognized as a Supernova Remnant (SNR) producing optical and radio emission. The Russian astrophysicist I. S. Skhlovsky suggested in 1953 that radiation from Crab Nebula is produced by synchrotron emission of high energy electrons in its magnetic field. Soon after, the discovery of polarization of optical and radio radiation from Crab Nebula confirmed this hypothesis. In 1967, radio pulsars were discovered and their pulsed radio emission was explained as synchrotron emission of electrons accelerated to energies of 10^{13}–10^{14} eV by the extremely high electric fields generated in the polar cap regions of the pulsar. Discovery of 33 ms radio pulsations from a source NPO 535 + 26 located in Crab Nebula in 1968, followed by detection of pulsed X-ray emission from it soon afterwards confirmed the general validity of the pulsar model.

It was argued that if electrons can be accelerated to energies of tens of TeV, protons of comparable energies must also exist in Crab Nebula. These energetic protons will undergo *p*–*p* collisions producing charged and neutral π-mesons. The neutral π-mesons will decay into 2ϒ-rays with energy of GeV to TeV. Crab Nebula and its pulsar were thus predicted to be sources of very high energy ϒ-rays. Gamma-rays of TeV and higher energy will undergo pair production as they travel in the atmosphere and develop into a shower of electrons similar to the known extensive air showers produced by cosmic ray protons.

This shower of high energy electrons will produce a cone of Cerenkov light as it propagates deeper into the atmosphere. Gamma-rays of TeV energy from the Crab Nebula and other similar objects should thus be detectable at mountain altitudes by measuring their Cerenkov light. Based on this reasoning, the TIFR group that included B. K. Chatterjee, G. T. Murthy, Ramanamurthy, S. K. Gupta, Sreekantan and Tonwar set up a Cerenkov experiment at Ooty in the mid-70s, consisting of a cluster of mirrors of about 1 to 1.5 m diameter each with a phototube at its focal point and operated in coincidence. The observations could be made only in clear dark nights.

After many months of observations they detected pulsed gamma-rays from the Crab Pulsar at about 4 б level and at a lower level from the 88 msec Vela pulsar. This emission was however not persistent and detected only sporadically. Due to unfavourable weather conditions at Ooty it was decided to set up a new Cerenkov telescope for TeV gamma-ray astronomy at Pachmarhi that has better observing nights. Ramanamurthy, P. R. Vishwanath, B. S. Acharya and P. N. Bhat were instrumental in setting up the Pachmarhi Cerenkov telescope. The Pachmarhi telescope was used for more than a decade to study TeV radiation from pulsars and also BL Lac sources Mrk 421 and Mrk 501.

About 10 years ago the European groups set up a Cerenkov telescope based on imaging technique that proved superior in rejecting the background due to proton-produced Cerenkov showers. This, coupled with order of magnitude larger areas of instruments like HESS and MAGIC, led to major breakthroughs in TeV gamma ray astronomy leading to detection of more than a hundred sources of TeV gamma-rays. Now TeV gamma ray astronomy is considered a mature area of experimental high energy astrophysics. The early work of Sreekantan and his colleagues played a significant role in the development of this field in India.

Sreekantan as Director of TIFR

M. G. K. Menon had become the director of TIFR after the sudden death of Homi Bhabha in an air crash in 1966. In mid-1974, he moved to Delhi as Chairman of the Electronics Commission. The question was, ‘who will succeed Menon?’. The TIFR Council found overwhelming support among TIFR Faculty in favour of Sreekantan. By then he had worked in TIFR for more than 25 years and had a solid reputation as a fine experimental researcher with outstanding leadership qualities, broad vision and ability to create and nurture new research programmes.

Sreekantan was appointed Director in January 1975. Over the next 12½ years he guided the institute with distinction and left behind a rich legacy of new research programmes and creation of autonomous TIFR Centres. His simplicity, sense of objectivity and fairness in the treatment of colleagues and other staff, generosity and accessibility to all, firmness when required and decisiveness won him platitudes from every quarter.

He not only strengthened the ongoing good research programmes but also encouraged and supported new initiatives. One such programme was the participation of TIFR in high energy physics research at the accelerator facilities in CERN (Geneva). Till the early seventies TIFR groups were engaged in high energy physics research based on studies of interaction of cosmic rays. By mid-seventies the focus shifted to accelerator-based studies of interactions of particles. It was clear that if TIFR wanted to continue front-ranking research work in high energy physics, it has to join in collaborative research at international facilities.

This was a major policy decision as it involved experiments located abroad and deputation of staff there. There were long discussions in the physics faculty and the opinion was divided. It was realized that the long term future of research in high energy physics lay in joining accelerator-based programmes and so one TIFR group joined the LEP experiment at CERN and a second group engaged in studies of cosmic rays deep underground, participated in D-Zero experiment at Fermi laboratory in USA. TIFR researchers built hardware for both the experiments and were deeply involved in data analysis. These programmes produced new and interesting results including the discovery of Top Quark at Fermilab. This paved the way in future for TIFR and other Indian groups to participate in the CMS experiment at the Large Hadron Collider (LHC) facility at CERN credited with the discovery of Higgs Boson.

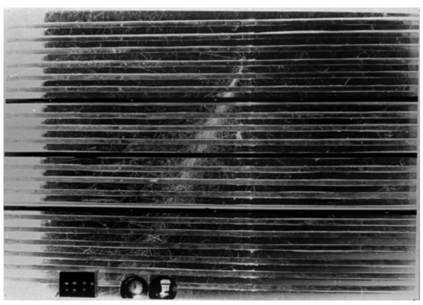


Image of a shower due to interaction of hadron in the Big Multi-plate Cloud Chamber in the experiment at Ooty (Courtesy: J. Acharya, Photography Section, TIFR).

Sreekantan also played a key role in the creation and nurturing of facilities and TIFR centres located away from the Colaba campus. TIFR centres proposed by him in the Fifth Five-Year Plan of Government of India that came into existence either during his directorship or just before or after, are (a) Homi Bhabha Centre for Science Education (Mumbai), (b) National Centre for Biological Sciences (Bengaluru), (c) National Centre for Radio Astrophysics (Pune) and (d) TIFR Centre for Applicable Mathematics (Bengaluru).

The proposal for establishment of Pelletron Accelerator to be jointly operated by TIFR and BARC for nuclear physics research was also approved during his directorship. A major expansion and enhancement of technical facilities at TIFR Balloon Facility at Hyderabad was also carried out with his support during his tenure.

Sreekantan also encouraged Govind Swarup to come up with a proposal for a much larger and sensitive radio telescope that will be a worthy successor to the highly acclaimed Ooty Radio Telescope that Swarup and his team had built. This led to the setting up of the Giant Meter Wavelength Telescope (GMRT). Today, GMRT at Khodad near Pune, is among the most sensitive radio telescopes at meter wavelengths in the world producing outstanding science.

During Sreekantan’s directorship, he initiated several important and far-reaching measures for the welfare of staff that amply demonstrated his compassionate and caring nature and which earned him the love and admiration of TIFR staff. These included: (a) making contributory health service scheme of BARC accessible for TIFR staff and their families; (b) a pension scheme for retired TIFR staff; (c) constructing staff quarters at the BARC-owned land at Mankhurd; (d) subsidized housing loan to employees; and (e) career advancement measures especially for lower staff like watchmen, drivers, and other support and auxiliary staff. Every morning, on his way to office from his Director’s flat in the TIFR housing complex, he would invariably go around the housing complex, institute building workshop area, etc. to ensure their proper maintenance.

Due to his sterling qualities of head and heart Sreekantan proved to be a popular Director, liked by all. After an eventful tenure of 12½ years Sreekantan laid down office in August 1987 at the age of 62 years. After retirement as Director, he was awarded the INSA Srinivasa Ramanaujan Professorship. He held this chair till 1992 devoting himself to research and then moved to settle down in Bengaluru.

Sreekantan was honoured on his 60th Birthday in 1985 with a Festschrift entitled *Cosmic Pathways: Contemporary Perspectives in Physics and Astrophysics* (edited by Ramnath Cowsik) brought out by his colleagues and students. This included articles related to him and his work in cosmic rays and astrophysics from his numerous national and international colleagues and students[2].

Sreekantan's association with Indian Institute of Astrophysics and contributions to its development

Sreekantan had a close association with Indian Institute of Astrophysics (IIA), Bengaluru since the days of Vainu Bappu, the founding Director of IIA. Till 1985 IIA was part of the Department of Meteorology under the Ministry of Civil Aviation. R. Ramanna and Sreekantan helped to bring it under the Department of Science and Technology (DST) as an autonomous institution. This facilitated its rapid growth and addition of new facilities. He was a member of the IIA Governing Council (GC) during 1988–92. When the 2.3 m Vainu Bappu Telescope faced teething technical difficulties, he reviewed the problems and helped evolving solutions. He served as Chairman of the IIA GC for 15 years during 1992–2007. Sreekantan believed in full freedom to the Director in running and managing the institution. He had excellent rapport with the Director. A major achievement of IIA during his chairmanship was the establishment of 2 m Himalayan Chandra Telescope (HCT) at Hanle in eastern Ladakh at an altitude of about 14000 ft. Teams from IIA under the guidance of the then Director R. Cowsik carried out an extensive survey for a suitable site and zeroed in on Hanle with good 'seeing' and clear skies. Establishment of infrastructure and facilities for a new observatory in a remote Himalayan location was a major challenge which was successfully achieved by Cowsik and Sreekantan.

IIA had no place at its Koramangala campus for further expansion and establishing new facilities. Land was obtained from Karnataka government and a second campus of IIA was established at Hoskote by Cowsik with strong support and assistance from Sreekantan. Today Hoskote campus houses HCT Remote Control Centre from where operation of the telescope is remotely carried out through a satellite link. The M. G. K. Menon Laboratory with clean-room facility for integration and testing of satellite payloads like Ultra Violet Imaging Telescope (UVIT) that will fly aboard *Astrosat* satellite, is also located at Hoskote. Housing facilities for the staff and new hostel for students also came into existence during the tenure of Sreekantan. He was always accessible to IIA staff and listened to their problems. His openness and sympathetic approach to human issues won him affection and respect of all in IIA.

Sreekantan's Work at National Institute of Advanced Studies, Bengaluru

In 1992 Sreekantan moved to Bengaluru and was immediately offered the Radhakrishnan Visiting Professor Chair at NIAS by the then director Raja Ramanna. His research interest now shifted from physical sciences to philosophical aspects of science and in particular to the abstract topic of consciousness and its scientific and philosophical basis. He explored commonalities in the approaches of science and ancient philosophies. He also probed the factors that contributed to the foundation and growth of modern science and organized two seminars on this at NIAS. Due to pioneering effort by him and the late R. L. Kapur, an internationally known psychiatrist, a multidisciplinary group at NIAS is studying consciousness and its scientific basis by applying physics and mathematics tools and models to understand information processing in biological systems. He continues to lecture at courses organized by NIAS for executives, managers and administrators sponsored by the industry and the government agencies.

While at NIAS he suffered a grievous personal loss when his soul mate Ratna passed away after a brief illness in 2006. This created a vacuum in his life but he philosophically accepted this as an inevitable process of life and continues to engross himself in the work at NIAS.

Awards and honours

In his long and distinguished research career Sreekantan received numerous awards and honours. The President of India conferred *Padma Bhushan* in 1988. He was given C. V. Raman award for Physical Sciences (1977) by UGC, the Homi Bhabha Medal for Physical Sciences (1978) by INSA, the R.D. Birla Memorial Award of Indian Physics Association in 1982 and the Ramanujan award of Indian Science Congress (1989). The Jawaharlal Nehru award of M.P. Govt was bestowed on him in 1991. He was decorated with Sir M. Visvesvaraya Sr Scientist State Award (2004) and the Rajyotsava Award by Karnataka Government. He was UGC National Lecturer in 1978 and received PMS Blackett Memorial Lecture Award of INSA–Royal Society in 1978.

He was elected Fellow of Indian Academy of Sciences, Bengaluru (1965); Indian National Science Academy, New Delhi (1976); National Academy of Sciences India, Allahabad (1989) and Maharashtra Academy of Science. Sreekantan is an Honorary Fellow of TIFR and IIA, Bengaluru. He was President of Indian Physics Association (1976–78) and President, Physics Section of Indian Science Congress (1981).

He served as Vice-Chairman of IUPAP Cosmic Ray Commission (1987–93), Member of Atomic Energy Commission (1985-86) and Chairman of the Research Council of National Physical Laboratory, New Delhi. He was Editorial Fellow of the project 'History of Indian Science, Philosophy and Culture' and is at present Chairman of the Gandhi Centre for Science and Human Values of Bharti Vidya Bhavan at Bengaluru.

Sreekantan's research colleagues and students

Sreekantan mentored a large number of researchers in cosmic rays and their interaction as well as in X-ray Astronomy during his career at TIFR. His prominent colleagues in cosmic ray work at TIFR include S. Naranan, P. V. Ramanamurthy, A. Subramaniam, V. S. Narasimham, G. S. Gokhale and S. V. Damle in balloon-borne astronomy. They rose to become leaders of their respective research groups. He supervised the Ph D work of B. K. Chatterjee, G. T. Murthy, M. V. S. Rao, Siddeshwar Lal, S. C. Tonwar and R. H. Vatcha in cosmic rays and their interactions. Though not an official guide, he was de facto thesis guide of P. C. Agrawal, and R. K. Manchanda in X-ray astronomy.

Publications

Sreekantan has authored nearly 300 research papers and articles in well-known physics and astrophysics journals, proceedings of international conferences and books. He has written or edited jointly the following books: 1. *Extensive Air Showers* (with M. V. S. Rao), World Scientific 1998; 2. *Remembering Einstein: Lectures on Physics and Astrophysics*, Oxford University Press, 2010; 3. *Interdisciplinary Perspectives on Consciousness and the Self* (with Sangeetha Menon, Anindya Sinha), Springer, 2014; 4. *Nature's Longest Threads: New Frontiers in Mathematics and Physics of Information in Biology* (with Janaki Balkrishnan), World Scientific, 2014.

Epilogue

Sreekantan will soon be completing 9th decade of his remarkable life in which he has contributed enormously to the development of experimental cosmic ray and high energy physics and astronomy. Two generations of scientists have been trained and mentored under his benevolent leadership. Before ending this article I wish him on behalf of his numerous colleagues, students and admirers continued good health, happiness and an intellectually active life. May he complete a century and continue to provide his wise counsel and serve as a beacon of inspiration to the young researchers.

Acknowledgements

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