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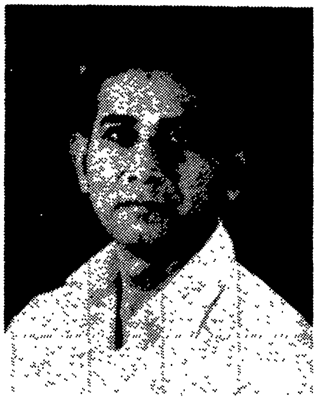

Cosmic rays, x-ray astronomy and Be stars – A career of research in astronomy

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When the Editor of the Bulletin asked me to write an article on my work with autobiographical notes, I was surprised and was inclined to say no, because this kind of request is usually reserved for researchers with outstanding work. Then I realised that even a person of very modest achievements can convey the excitement and enjoyment felt during the years of work and especially recall the moments of exhilaration when one finds solutions to problems, though small and not earth-shaking. The hope is that this might give some encouragement to young people who are starting their career in research and not aggressive enough to think that they can conquer the world or get the Nobel Prize. In the following I will give an account of some of my work... I will not write about all the papers I published... and some of my experiences.

Particle physics and cosmic rays

In the 1950's elementary particle physics was just starting. π-mesons were discovered. The advent of Nuclear Photographic Emulsion plates made the tracks of charged particles visible. The tracks produced in the nuclear emulsion could be seen under a microscope. The Cosmic Ray Group at the Tata Institute of Fundamental Research got interested in studying these particles. As a new recruit I was assigned the job of scanning the plates for unusual tracks. There was excitement and anticipation of discoveries in the air and all of us spent days and nights looking into the microscope. The camaraderie was exceptional and made one bear the tedium (sometimes) of looking through a microscope hours on end. When some one found something interesting, he or she would shout 'Mila Hai', and everyone crowded around to see what it was.

The Nuclear Emulsion group, as it was called then, found many interesting things – the physics of the τ-meson, the Hyperon decay, and their associated production, the charged θ-meson. The identification of the last one formed the subject of my first research paper – I was walking on air for a few days because it was my first paper and because the word 'discovery' was associated with this work. Much later I found that there are discoveries and there are discoveries – some monumental and some pedestrian – the word is used by many just to draw attention.

Particle physics was later taken over by accelerators, which produced various particles more copiously than could be produced by cosmic rays. We all then reverted to the original interest of the group, namely research in Cosmic Rays (CR). The fifties and sixties were times of new findings in CR. It was known that CR contained protons and α-particles (He nuclei). Heavier nuclei were also found in CR and we undertook the task of finding the abundance of these. It was found that compared to their Universal abundances, Li, Be, B, C, N, O, and other heavier nuclei were more abundant in cosmic rays. Also the abundances of the light nuclei Li, B and Be are negligible in the Universe, when compared to that of C, N, O nuclei. So it was surmised that these light nuclei in cosmic rays are products of spallation of cosmic ray C, N, O, when they collide with the interstellar gas during their travel from their source to the earth. This gave us a measure of the amount of interstellar matter through which cosmic rays have passed. The setting up and solving the diffusion equations was my first "theoretical" task. There was of course the task of searching these nuclei in the photographic emulsions and measuring their charges. All this work was done with other colleagues.

We had respite from the long hours of scanning, by going on field trips to fly balloons. Cosmic Rays which arrive from outer space collide with air nuclei and those with low energy are absorbed by the top layers of the atmosphere. So to catch them one had to fly stacks of nuclear emulsion to great heights by means of balloons. This balloon flying was a great adventure. The stacks of emulsion were attached to a parachute which was then attached to a big balloon (now-a-days they can be ten storeys high or higher) which was filled with hydrogen. Though this may sound simple, the filling operation and release requires several people with skill and luck too!. The balloon rises to high altitudes and floats. After some time the balloon is cut off by a clock and the emulsion stack comes down by parachute. To get back the stack, however, we had to keep track of the balloon through telescopes to know where it headed. Many a time the stack landed in remote areas or forests. Then a search team went and rescued the packages. (the adventures during the recovery, in which I too participated, need another chronicle).

Discovery of He^3 isotope in cosmic rays

I did my Ph.D work at the University of Rochester, U.S.A. While doing the course work I was allowed to continue my research. I devised a way of finding the mass of a helium nucleus from its track in a nuclear emulsion and applied it to Cosmic Rays. I was the first to do isotopic analysis of Cosmic Ray nuclei. Using the observed helium tracks in an emulsion stack exposed to cosmic rays at high altitudes, I determined the masses of the helium nuclei. To my surprise, I found the tracks of helium-3 isotope. The abundance of He^3 isotope is negligible when compared to the abundance of He^4 isotope in the Universe. So the observed He^3 nuclei must be due to spallation of He^4 nuclei as they travel from the source of cosmic rays to the earth. Using the observed He^3/He^4 ratio I determined the amount of the interstellar matter traversed by cosmic rays. Presenting the results at an International conference and receiving compliments were new experiences. This work formed my Ph.D thesis.

An interesting episode in U.S.A.: Just for fun

I estimated the albedo of neutrons when Cosmic rays hit the Moon's surface (since the moon is not protected by a magnetic field as we are) and published the results in the journal 'Science'. A few days later, I got a call from a reporter of the New York Times and he asked me several questions. Next day a news item appeared in the New York Times with a head line 'Scientist Predicts Radiation Geysers on the Moon'. Soon after somebody called me from NASA asking for my paper and wanted to know if these neutrons could harm Astronauts. I assured him that they would not, except during solar flares, when, of course, the solar particles themselves could be dangerous.

Back at TIFR, I pursued several investigations related to the propagation of cosmic rays in the interstellar and the interplanetary space, with the aim to understand their modification during their traversal. From this the composition at the 'source' of cosmic Rays could be determined. I also had my hand in building an electronic device to measure the composition of Cosmic Ray heavy nuclei. Playing with the then new spark chambers was a mixture of fun and frustration.

Crab Nebula

My attention however wandered to other problems in Astrophysics. The Crab Nebula, in particular, fascinated me. It is an extremely interesting object, radiates at all wavelengths and has a pulsar and so on. (I wrote a review on Crab Nebula for Space Science Reviews) It was well established from radio observations, (the radio emission was interpreted as synchrotron emission) that it has high energy electrons. I thought that the then newly discovered Universal 3° Kelvin microwave radiation can be scattered off these high energy electrons which by the inverse Compton process can generate gamma rays of energy upto 10^{12} ev. I calculated and wrote a paper. Those days, there was a move to 'build up' Indian journals and all the papers from our group were sent to an Indian Journal. The paper did not receive the attention it deserved although it was extensively used in other contexts, especially in the extragalactic context.

Antiprotons

Another interesting investigation I made at this time was a search for anti-protons. Alfven was arguing that the Universe contained antimatter. So I thought that antimatter should show up in cosmic rays. I devised a way of identifying antiprotons in low energy cosmic rays, using their tracks in nuclear photograph emulsions. These emulsions were exposed to cosmic rays at high altitudes. The procedure, however, involved a laborious search for these tracks with the required signature. I had the help of three professional scanners. Each day we started with the hope of finding an antiproton track. This went on for six months and then I gave up hope, and stopped the project; I gave an upper limit on the abundance of antiprotons in cosmic rays. A decade later antiprotons were discovered in cosmic rays using electronic instruments. The flux of antiprotons was such that had I continued the search for another four months, I would have found a track of an antiproton. Bad luck!... or may be not... I got a promotion for devising this search.

Another near miss

Pulsars were newly discovered at Cambridge, England while I was at the other Cambridge (U.S.A.) at the Harvard College observatory. I tried to see whether cosmic rays could come from pulsars, since high energy particles are accelerated there. Later, I tried to see if pulsars contribute to the background X-radiation. Also, Jeff Hoffmann (then a graduate student, now an astronaut, who flew in the Shuttle and repaired the half-blind Hubble Telescope) and I had shown that the gamma rays observed from the Crab pulsar could be due to Compton-synchrotron emission near the light circle of the pulsar. While I was at Harvard, one day I was looking at the data on the compact radio source in the Crab Nebula. From the steep spectrum and its compactness, I surmised that it could be a pulsar (Crab pulsar was not discovered then). I was on my way to see Joseph Taylor (later winner of Nobel Prize for pulsar research), who worked in a neighbouring building, to discuss this. My next door neighbour met me in the corridor and asked me where I was rushing to. I told him my surmise about a pulsar in the Crab. He said that Pacini had published a paper in Nature why a pulsar in the Crab cannot be seen and gave me a reference. I went to the library and saw the paper (Pacini argued that the pulses will be smeared to form a continuum). Though not quite convinced, I dropped the idea of seeing Joseph Taylor; subsequently, the Crab pulsar was discovered.

X-Ray astronomy

In the early seventies, x-ray astronomy was a new and exciting field. Different kinds of x-ray sources were being discovered and every one was talking of neutron stars and black holes. I was lucky to be at the Centre for Space Research, Massachussetts Institute of Technology (MIT), Cambridge, U.S.A. At that time they had a satellite with x-ray detectors (SAS–3) in the orbit. I was a part of the group which determined the locations of the x-ray sources within 20 arc seconds using a Rotation-Modulation Collimator. This allowed us to identify the x-ray emitting objects with their optical counterparts. Among these optical counterparts were the Be stars, which I will discuss later. X-ray sources which gave out bursts, were found at MIT using the SAS-3 satellite. This was an exciting time, for new facts were revealed and discoveries made almost every week. Several x-ray pulsars were found and their periods were determined. We also identified a low redshift quasar as an x-ray source.

Fun and panic with a satellite

It was interesting that the satellite SAS-3 was being controlled by physicists. The physicists determined the orientation of the satellite. Also the orientation of the solar panels, the instrumental apertures and filters were all decided by physicists. That meant a duty scientist was there all the twenty four hours. The physicists took 8 hour shifts and I also had my share of the shifts. The duty consisted of making the codes for positioning and other functions and faxing this information to a technician at the Goddard Space Flight Centre located near Washington, D.C. He, in turn, sent the codes through his computers to a computer in Brazil, South America via a geocentric satellite. The x-ray satellite was revolving around the equator (put in equatorial orbit to reduce backgrounds) and when it was "in view" (for about 15 minutes) the computers in Brazil sent up the coded commands for carrying out various functions. Also, it sent down the data collected by the instruments (recorded by tape recorders) to the computers in Brazil, which then sent it back by the same route .... geocentric satellite, to the Goddard Space Flight Centre and by telephone line to MIT ..... to the computers at MIT. The computers at MIT displayed the data for the perusal of the duty scientist who then stored the data. This happened every 90 minutes which was the orbital period of the satellite.

Two incidents stand vividly in my memory: the first, when I was a duty scientist during the graveyard shift (12 midnight to 8 am). I gave a routine instruction for changing the orientation of the satellite a little and sent it to Goddard. After a while the technician at Goddard called me and told me that a wrong instruction has been sent by mistake and asked me what should he do. I calculated to see what the wrong instruction would do and found to my horror that the X-ray instruments would "look" at the sun which would ruin them (I did not know at that time that if this orientation happens, there were fail-safe devices which drive the satellite into a mode called 'tach-mode' in which the satellite spins rapidly and protects the instruments). I did not know what to do and started calling the MIT satellite expert at home in the wee hours of the morning. He asked me to calm down and asked me to calculate the right orientation and send it to computers in Guam, an island located in the Pacific Ocean, where the satellite comes in "sight" after the passage over Brazil. The computers in Gaum will load the fresh signals into the satellite. This was done and all was well, but for a while I thought I had ruined the 25 million dollar satellite. The second interesting incident occurred when I was the duty scientist. I noticed from the computer display that an X-ray source was flaring. However, to see the flaring best, the satellite had to be moved ever so slightly. If the regular procedure of sending the corrections through the usual route were used we would lose one orbit or ninety minutes of time. So I communicated to the Goddard technician that we would do the correction while the satellite was "in view" over Brazil. I was to give the instructions over the phone to the technician who will press the right buttons to send signals through the geocentric satellite. We agreed that R3 means movement of the satellite to the right by three arc seconds and L2 means movement to the left by two arc seconds and so on. When the satellite came "in view", it was sending data which the MIT computers displayed, looking at the data and after a few R's and L's we got the instruments looking exactly at the source to receive the maximum intensity. To this day, I marvel how the satellite so far away in space was controlled by me, through the long chain of communication .... telephone to Goddard, through a geocentric satellite and through computers in South America!

Neutron stars, cyclotron lines, Cyg X-1

The x-ray astronomy flourished during the seventies and eighties. Modelling the x-ray sources using white dwarf stars and neutron stars has been an interesting project for me. On seeing a paper on cooling of neutron stars, I though that some of the neutron stars which function as the pulsars may still be hot enough to give x-rays. I proposed that the x-rays from the nearby pulsars could be due to the black body radiation from hot neutron stars. It took another decade when instruments on board the satellites became sensitive enough to detect and identify this black body radiation.

The accepted model for strong x-ray sources is that a neutron star orbits around a normal star to form a close binary. The normal star fills its Roche lobe and matter overflows into the Roche lobe of the neutron star. An accretion disk forms around the neutron star. The accretion is stopped at the magnetosphere of the neutron star. the matter then is guided by the magnetic field towards the poles of the neutron star, where the gravitational energy of the unfalling matter to thermal energy which is radiated as x-rays. Neutron stars, however, have strong magnetic fields (10^{12} gauss and higher) and electron cyclotron radiation must originate at the poles. The electron cyclotron line, for the high neutron star magnetic fields, falls in the x-ray region and was observed. Kumar Chitre, Martin Rees and I thought that protons also should emit cyclotron radiation near the poles of accreting neutron stars. This line radiation is in the EUV and UV region for the strong magnetic fields under consideration. However, the fundamental and several harmonics are all absorbed by the emitting gas itself. As a result only harmonics of large number escape the gas and the resulting radiation looks like a black body radiation. Such radiation was observed from the x-ray source Her X-1 and several other x-ray sources. Kumar Chitre and I also investigated helium cyclotron emission. This occurs in the UV region and is observable. Unfortunately, the radiation is weak and requires special circumstances like proximity for its observations.

The X-ray source Cyg X-1 shows two phases of intensity - the high and the low. During the high state the spectrum is soft and during the low state it is hard. It is believed that Cyg X-1 has a black hole at its centre instead of a neutron star. The black hole orbits around an early type star which feeds matter to the black hole through accretion. The accretion disk gets quite close to the black hole before being swallowed, and the matter reaches very high temperatures ($T_e \sim 10^9$ °K). Here, I suggested that the electrons give out cyclotron radiation in the ambient magnetic field and this radiation is in the UV region. This radiation is upgraded in energy to x-rays by inverse Compton process while it passes through the hot disk. I found that the Comptonized flux is inversely related to the matter accretion rate thus explaining the nature of the spectrum during high and low states of Cyg X-1.

Moscow, Leningrad

One of the perks of a research career is that you get opportunities to travel to attend meetings and conferences. Thus, I got to see most of the world. The trip to Moscow and Leningrad is a memorable one. Two Russian astrophysicists, Yuri Gnedin and George Pavlov visited our Institute under a Indo-Russian programme. We did some work together and published a paper on radiation from the polar region of an accreting neutron star. I was invited to Russia reciprocally under the Indo-Russian programme. When I was in Moscow, I met Academician Ginzburg, who gave me a tour of their Institute. In Moscow I was given a guide, who took me around to see various places. I went around by myself too to see how Russians lived. I saw long queues and was told that whenever some scarce item arrived at a store, people lined up. Next I went to Leningrad and was put up in a grand hotel. Yuri Gnedin showed me around. A visit to The Hermitage, a museum containing Russian treasures, was memorable. Of course, it was not all fun–I gave some lectures and had some interesting discussions with various astrophysicists.

Infrared bursts

Some x-ray sources give x-radiation in the form of bursts. These bursts occur with time intervals of several hours to days between them. There is one burst source, however, which gives bursts with intervals of several minutes. This is called the Rapid Burster. An interesting fact about it is that the interval between the bursts depends on the strength of the preceding burst. Kumar Chitre and I suggested a model in which the phenomenon originates near the polar regions of the neutron star. The accreting matter guided by the magnetic field arrives at the poles of the neutron star as a column. The accreting matter as it falls on to the surface forms a shock where energy is released in the form of x-rays. The radiation pressure drives the matter upwards and the shock occurs higher. At larger heights the energy release is not enough to heat the matter to sufficient temperatures to give x-rays and the x-ray emission, therefore, ceases. The radiation below the shock escapes from the sides and the matter falls back and the shock gets nearer to the surface of the neutron star and x-ray emission commences. Thus the x-ray emission occurs in bursts. Kumar and I proposed that cyclotron masering should take place in this object. We found that the emission occurs in the infrared region. Thus, there should be infrared bursts. We approached P.V. Kulkarni of Physical Research Laboratory, who had an infrared detector. Vainu Bappu was enthusiastic about the observation and he gave us time on the one meter telescope at Kavalur. On one night the telescope was trained on the Rapid Burster and all the infrared instruments were turned on. With eager expectations, we were looking at the chart recorder and were disappointed to find a flat line. We suspected our surmise. However, after two hours, someone shouted "there is something" and there it was, a perfect burst with a fast rise and an exponential decay. Kulkarni assured us that it was not instrumental; later that night we saw three more bursts. It was thrilling to see the bursts but we were puzzled that the bursts were not as frequent as expected in the Rapid Burster. We wrote this up as a 'Discovery' for the Journal Nature. We were encouraged to talk to the Press about the 'Discovery'; later we found that it was a mistake because the way it was printed, it gave more credit to us and produced an ill-feeling in our collaborators (NEVER GO TO THE PRESS - they usually distort what you say and cause embarrassment) The infrared bursts were later confirmed by observers at Tenerife, in the Canary Islands, and by Kulkarni and associates who went again for observation of the Rapid Burster.

Catwalk

When observing at telescopes at night, there were always some breaks during which I often went on to the "catwalk", which is an iron walkway around the dome of the telescope. The telescopes at Kavalur are on a tower and while on the catwalk one feels suspended in air. There was always a cool breeze. There was darkness all around and as you look up at the sky studded with stars, some blazing like diamonds, one feels a sense of peace ... a feeling of being one with the Universe .... a sort of a mystical feeling. Try going on the catwalk next time you happen to be at a telescope.

Cyg X-3

Even while attempting to explain phenomenon in x-ray Astronomy, my attention always strayed to problems in cosmic rays and gamma ray astronomy. Cyg X-3 is an interesting x-ray object. It gives strong radio bursts and gamma rays have also been observed from it. I explained the gamma ray emission as inverse Compton scattering of the x-ray photons by the radio producing high energy electrons. The x-ray emission occurs with a period of about 4.8 hours, but the radio emission occurs with a slightly different period. I suggested that the radio emission occurs from electrons accelerated by the Compton process by the x-rays and gamma rays impinging on clumps of matter in a cocoon around the object. The radio period turns out to be the beat period between the x-ray period and the orbital period of the clumps.

Gamma ray bursts

Gamma ray bursts coming from outer space were observed by instruments aboard many satellites. With the help of several satellites a triangulation was done to obtain the location of a few bursts with error circles of a few minutes. Surprisingly there were no optical objects in the error circle. The model in vogue at that time was that of a neutron star in a binary orbit producing the burst. Since the optical object was not seen, I surmised that the binary companion to the neutron star must be as faint as an M spectral type (not visible in the optical due to the large distance); M stars also give flares, which could lead to the bursts. M stars can be observed in the infrared due to their low surface temperature. I got time on the 4 meter telescope of the Anglo Australian Observatory to observe the gamma ray burst error circles in the infrared along with David Allen. I was looking forward to going to Australia for the observation and a possible 'discovery'. But before I went for the observation Allen got eager and impatient and swapped the time with somebody and made the observation. No infrared object was seen and we could place stringent limits on various things. But for a while there was excitement that something might show up.

Cosmic rays again

One interesting piece of work in cosmic rays was an explanation of the over abundance of heavy nuclei as compared to their Universal abundances. Shankar Tarafdar (Dada) and myself noticed that the condensation temperature and the abundance of heavy nuclei correlate well. Our suggestion was that these heavy nuclei are solidified to form grains in envelopes around the pre-supernova star. The supernova explosion first melts these particles and then accelerates by means of the blast wave. Whether this is correct or not, the correlation between the condensation temperature and over abundance is intriguing.

White holes

N. Dadich and Jayant Narlikar found, by solving some equations in general relativity, that there could be a situation where matter can be expanding out from a singularity which is the reverse of the process of formation of a black hole. The obvious name for this object is "White Hole". I joined them in the search of such white holes. We suggested that many observed high energy phenomena could indeed originate from white holes. Jayant and I further expanded this work to account for the energy in the radiation from quasars, active galactic nuclei and gamma ray bursts. We also thought that the inward rush of the matter during the formation of a black hole may be stopped and can be reversed by a repulsive field. (the C-field was earlier introduced in other contexts by Hoyle and Narlikar). This expanding matter after reversal will be a white hole. The gravitational field after some time will stop the expansion and reverses the motion of the gas again, to make the matter fall in. Thus black hole - white hole - black hole - .... oscillations may occur. We used this kind of oscillations as an energy source for quasars and other high energy phenomenon. This could indeed account for bursts of energy released in these objects. Jayant and myself again thought that this kind of oscillation might be taking place in the case of our Universe. The Big Bang will be the white hole phase. We considered the nucleosynthesis in the case of this Bouncing Cosmology.

Planetary nebulae

In the 1980's several satellites bearing sensitive x-ray detectors were flown and they collected a large volume of data. Scientists who built the instruments were alloted a lot of proprietary time, which they filled with proposals to observe literally every object in the sky. Many of them had no time to look at the data; they were usually off and away making more proposals and more instruments. So it is a field day for those who can use the data and we found it extremely profitable. One such useful piece of work we did was the study of x-ray emission from planetary nebulae. Dada and myself collected observations from the Einstein observatory and analysed the data of nineteen planetary nebulae. Four of them were found to be emitting x-rays. We assumed that the emission was from the central star and determined its temperature from the x-ray flux along with the optical data. We found the temperature agreed with the Helium Zanstra temperature. We also used another detector on the Einstein observatory to show that the x-ray emission is indeed from a point source which coincides with the central star. Later, using data from the EXOSAT satellite, we found some more planetary nebulae with x-ray emitting nuclei. While I was at Penn State University, much later, I found data on two planetary nebulae with binary nuclei out of which one emitted x-rays copiously. We found binarity had no influence on the x-ray emission from the central star.

With Vainu Bappu

I had met Vainu Bappu many times over the years. But two meetings stand vividly in my memory. The first was when I went to Kavalur to pick up a mirror for use in the infrared instrument to be flown in balloons by our group at TIFR. In the evening I went to the telescope dome where Bappu was observing. During a break, he started explaining his observations, and then drifted to observations of quasars. It was very educational for me, but what struck me was his lucidity and enthusiasm for observations and also the way he treated me as an equal in discussions. He never had any airs. The second was at the ESO observatory in Garching, Germany. I was attending a meeting there and was lodged in a guest room attached to the observatory. On a Sunday I went to the library near the observatory and saw Bappu (there was no one else around). He greeted me and said "Come, I will show you some interesting things". He took me to a place in the observatory where there was a plate scanner with computers. He put some spectroscopic plates exposed to γCas. He pressed some keys on the computer keyboard and showed me the spectral lines displayed on the computer screen. He told me how in the earlier days, they had to laboriously measure things with microscopes, and how, now, everything is automated, and with the help of computers one could do tricks like zooming etc. There was an almost childlike enthusiasm and delight in the way he manipulated things with the computer. This was when he went for his bypass surgery at Munich; I did not know it then. I was shocked to hear of his demise a few weeks later. But I treasure the memory of the two encounters.

Be stars

When we obtained the positions of x-ray emitting objects with the instruments in the SAS-3 satellite, several B-emission line (Be) stars appeared in the error circles. Some of them showed pulsation in their x-ray emission indicating the presence of a neutron star, suggesting a binary system of a Be star and a neutron star. These Be-x-ray systems were found to be transient i.e. that they emit x-radiation for a while and then cease for extended periods. One of the Be x-ray sources A0538-66 showed flaring every 16.5 days. I got intrigued by this and made a model to explain this behaviour. But first a little description of Be stars. B stars have a mass in the range ~3 to 20 $M_\odot$ and have surface temperatures in the range ~11,000 to 30,000°K. They normally show absorption lines in their spectra. But some of them show emission lines occasionally. The emission line are H_α, H_β and other Balmer lines, HeI lines, FeII and some other singly ionized metal lines. These lines appear, increase in strength and slowly fade away. This behaviour is interpreted as due to formation of a gas envelope around the star, which gives the emission lines and which later dissipates. Be stars have a large rotational velocity as compared to B stars. Therefore it was postulated earlier that Be stars have an extended gas envelope around the equatorial regions. Chitre, Antia and I suggested that the Be stars have a fast rotating core which "convects" angular momentum to the surface. This additional angular momentum destabilises the fast rotating outer layers, leading to the ejection of matter in the equatorial region.

The model I considered for the x-ray emission of A0538-66 was a binary system consisting of a neutron star and a Be star. The Be star emits a gas disk which is confined to the equatorial region and expands outwards. The disk density structure was assumed. When the expanding disk encounters the neutron star, accretion of matter on to the neutron star takes place with consequent x-ray emission. However, to explain the flaring behaviour, it was suggested that the orbit of the neutron star is eccentric with an orbital period of 16.5 days. In order to explain the flare structure, the orbit of the neutron star was also suggested to be inclined to the plane of the disk. The intensity of the flares and their structure could successfully be explained by the above model. Later on the model was applied to several other Be x-ray sources with different flare structures.

Energy crisis in Be stars?

I got together with Dada to learn more about stars, radiation transfer and various aspects of classical astrophysics. He was a patient teacher and my collaborator for the last decade or so and

I am grateful to him. As I learnt more about Be stars, I found a wealth of optical and ultraviolet data. There were models explaining the line structure (the lines are usually wide, some are double peaked, some bottle shaped and so on.) Everyone in this field assumed that the radiation from the Be star ionized the matter in the gas envelope which then emitted the lines. But nobody was concerned about the energetics of the lines. This is probably because all the line emissions were expressed in equivalent widths and stellar brightnesses were given in magnitudes. The line strengths and stellar brightnesses were not expressed in so many ergs s^{-1}, as we are used to in x-ray astronomy. So Dada and I set ourselves to examine this question — is there enough Lyman continuum radiation to energise the line emission? The first line, we investigated, was H_α; we calculated the energy in the emission of the line for different spectral types using the Lyman continuum photon numbers given by model atmosphere calculations. Comparing with observations we found that the calculated values fell short of the observed values for spectral types greater than B5. We tried to see if we can enhance the ionization by absorbing Balmer continuum photons. The Lyman continuum keeps a certain number of hydrogen atoms in the n=2 state and these can absorb Balmer photons to get ionized. Dada's expertise in radiation transfer in these calculation was important. Though this Balmer photon absorption enhanced the ionization a little it did not help the situation. Recently we have suggested that these late type stars which show H_α emission have a Helium star as a binary companion. He stars are hot and have temperatures ranging form 35000°K to 75000°K. They have enough ionising radiation to give the observed H_α emission and we have shown this by calculation. The same situation arises with HeI 5876 line. The Be star radiation can produce enough HeI line emission for stars of spectral type earlier than B1 and is not enough for later types. Again a compact companion (white dwarf or He star) is needed to provide the HeI ionizing radiation (these compact stars are not observable in the optical region due to the glare of the brighter Be star). This raised an interesting question - are all the observed later types of Be stars binaries? Or may be only those Be stars (of later types) with a compact companion will show up as line emitting objects. Further observations are needed to settle the question.

The observations in the far–infrared by the IRAS satellite have been used by several authors to obtain the emission measure of the emitting gas in Be star envelopes. We used these emission measures to calculate the expected H_α emission from various spectral types. We found these values are far in excess of those observed. Be star radiation is highly variable and the infrared and H_α measurements were made at different times. We wondered whether the non-simultaneity of the observation could be the reason. To verify this we went to Kavalur with several colleagues (K.K. Ghosh has been an important collaborator in our observation of Be stars) and measured simultaneously the infrared flux (on the 30 inch telescope) and the H_α flux (on the 40 inch telescope). We found the discrepancy still existed. We then surmised and calculated (by radiation transfer equations) that H_α line was self-absorbed in the case of large emission measures and shown it to be so. We further found out that in the case of Paschen line emission the gas is optically thin and the calculated emission measure agrees well with that obtained from the infrared observation. This indicates that both the H_α line and the infrared emission arise from the same ionized gas. However, we noticed that the Lyman continuum of the Be stars is not enough, for all spectral types, to account for the emission measures obtained from the infrared observations. Again the enhancement by Balmer photon absorption did not help. Recently, the instruments aboard the EUVE satellite have measured the far ultra violet flux from the star ϵ Canis Majoris, which is a B2 star (not a Be star) and found that the observed flux is about 30 times that given by stellar atmosphere calculations. This would be enough to account for the observed emission measures derived from the infrared observations. Do such fluxes occur in Be stars of later spectral types? How do these large fluxes arise (theory of stellar atmospheres has to be modified drastically!)? Or may be this star also has a compact companion. We have to wait for further theoretical and observational progress in order to answer these questions.

Be stars also show CII, FeII and Ca II (triplet) line emission. These lines cannot arise from the ionized region because the relevant elements occur here in higher ionised states due to the high temperature in the HII region. We surmised that the gas disk is thick and that the whole disk is not ionised by the Be star radiation. A cooler part of the disk exists, where the sub-Lyman ultraviolet photons can lead to singly ionized metals. This region is called the CII region, as CII is the most abundant ion here and supplies the electrons for recombination. Dada applied his expertise in setting up and solving the complicated radiation transfer equations. We could explain the FeII, CII and CaII triplet line observations. In the case of CII the lines were observed by K.K. Ghosh during a flare of the star HR4123 and interestingly the process which explains the emission is dielectronic recombination. In the case of the CaII triplet, the line intensities were observed to be the same, instead of being proportional to their recombination values. It turns out that this CII region is optically thick for these lines resulting in the similarity of the intensities.

Be stars show very interesting long term optical variations, both in the continuum and line emission. Sometimes the brightness of the star suddenly decreases by half a magnitude or more. We are exploring the formation of dust in the disk as it expands away from the star, which can obscure part of the star leading to a decrease in brightness. There are many other unexplained observations of Be stars and this will keep us busy for a long time.

Looking back, looking forward

Looking back on more than forty years of research in Cosmic rays, x-ray astronomy and Be star Astrophysics, I see a happy fun-filled research career with interesting experiences. Looking forward there is no dearth of interesting problems to work on ..... especially in Be star physics. Also just keeping track of new discoveries through e-mail and journals is absorbing. I enthusiastically recommend research in Astronomy and Astrophysics to young people.

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