S. Chandrasekhar

SUBRAMANYAN CHANDRASEKHAR

(1910-1995)

Elected Foreign Fellow 1962

SUBRAMANYAN CHANDRASEKHAR was born in Lahore on October 19, 1910. His father C Subramanyan Ayyar was Assistant Auditor General of Northern Railways posted at Lahore. Chandra was number three in a family of 10 children; 4 sons and 6 daughters. In 1916, the family moved to Lucknow and in 1918 to Madras where his father was posted as Deputy Accountant General. Chandra's education started at home in a very disciplined manner. His father used to teach him in the morning before he went to the office and his mother used to teach him Tamil. Chandra enjoyed learning English, and Arithmatic caught his fancy. He was sent to a regular school only when he was eleven. Chandra, though young, showed considerable maturity and understanding. He liked mathematical physics more than pure mathematics and he was determined to pursue pure science.

As a student of BA he had learnt the German language sufficiently well to be able to grasp Pauli's article on Quantum Mechanics in the Handbuch der Physik. While a student he had submitted a complex theoretical paper to the *"Astrophysical Journal"*. On the advice of the reviewer the paper was rejected by the Editor. Back came a lofty letter from the young student : he conceded the right of the journal to reject his paper and merely wanted to point out that the reviewer had been wrong. The paper was accepted.

Arnold Sommerfeld visited Madras in the fall of 1928 and lectured at the Presidency College, Madras. Chandra met him at his hotel and discussed some problems with him. With the deep mathematical preparation Chandra was able to complete a paper *"The Compton Scattering and the New Statistics"* and this paper was published in the *Proceedings of the Royal Society* in 1929. It is to be noted that he was only 18 at that time. The Principal of Presidency College, Madras recommended Chandra for a Government of India Scholarship to pursue his research in England. The scholarship matured about February 1930 and he received official intimation on May 22, 1930 and left Madras for Bombay on July 22, 1930. He left for England on Lloyd Trisetino on July 31, 1930. On the personal recommendation of Fowler, Chandra was admitted to Trinity on September 4, 1930. It is worth-mentioning that on his voyage, he had extended Fowler's work which led eventually to his own discovery of the celebrated critical mass condition the Chandrasekhar Mass Limit—on stellar masses that could become white dwarfs. He submitted his PhD thesis on *"Distorted Polytropes"* in May 1933 and was awarded the Degree in October 1933.

With the formality of the degree out of the way, Chandra was left only with the question of the future. He talked to Fowler and asked him whether there was any chance for him to stay an additional year in Cambridge. Fowler was not hopeful at all. He told him "No, I do not think there is any chance. You can try for a fellowship at Trinity, but the competition is quite severe. I doubt if you will get it". After some thinking, inspite of Fowler's discouraging remarks Chandra decided to apply for a fellowship, the outcome of which was to be decided in early October. A fellow of Trinity was a wild dream. The only other Indian who had been elected to a Trinity fellowship was Srinivasa Ramanujan some sixteen years earlier. The competition was formidable. It was open to candidates from all fields. Each candidate submitted a fellowship thesis containing an account of his work during the previous year and took two written examinations, one in general aspects of science and philosophy and the other in literature and the arts. Chandra submitted his thesis to Sir JJ Thomson, the Master of the college on August 24 and prepared himself for the examination on September 29, 1933. Chandra recalls as follows:

> *"I was so sure I would not get the fellowship that I had made arrangements with Milne to spend the fall months with him in Oxford. I had saved enough money from my scholarship to spend an extra three months in England. In September, 1933, I had gone to Oxford, rented a set of rooms for the fall and paid off my land-lady in Cambridge completely. I had even bought a bicycle because Oxford was a bigger place than Cambridge, but not big enough to use buses all the time".*

"On the day, 9th October 1933, the fellowship was to be announced. I took a taxi with all my things to go to Oxford, but on the way I stopped at the college to see who had been selected as Fellows. I was shocked to find my name on the list." Chandra recalls "when I saw my name, I remember telling myself quite loudly. "This is it, this changes my life". I went to the taxi and asked the driver to take me back to my rooms".

Milne, while congratulating Chandra in his letter dated October 9, 1933 wrote, "I believe that the election to a Trinity fellowship is one of the most important as well as the most gratifying events that can happen to one. I hope it will be a source of inspiration to you as it was to me, to be a member of such a society, to be part of those ancient and restful buildings, and to have your name inscribed in the roll which counts in its past so many names we all rever".

Chandra was quite thoughtful regarding his parents and family. In his letter dated October 12, 1933, Chandra writes to his father........ "during the whole of Sir JJ's speech last evening and during all the time, when so many people were congratulating me, there was only one picture before me - my mother in her Silk saree.... blessing me with all the force of her love to go forward'. Indeed I always have this vision which has been

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a great source of inspiration - intensely saddening, yet stimulating". Chandra's mother had passed away on May 21, 1931.

In December 1935, Chandra went to the United States for the first time, to lecture on theoretical astrophysics at Harvard College Observatory. Its Director, Harlow Shapley, impressed by Chandra's research, had invited him for three months, but after seeing him in action, wanted to keep him at Harvard as a research fellow. However, Otto Struve, the Director of Yerkes Observatory, the University of Chicago's astronomy outpost in Williams Bay, Wisconsin, was convinced that astrophysics, with theorists heavily involved, was the wave of the future. University President Robert M Hutchins had given him a free hand to make three appointments of the best astrophysicists he could find, demanding only that they be young. Struve had already signed up Gerald P Kuiper, an astrophysical observationalist, and Bengt Stromgren, a theorist to come in 1936. Both were foreigners, Kuiper from Holland and Stromgren from Denmark, while Struve himself had emigrated from Russia to the United States, arriving in 1921. In those days such appointments were rare in American Astronomy, which was dominated by old "native" stock. Kuiper, the leading observational authority on white dwarfs at the time and a former research fellow at Lick Observatory, was at Harvard when Chandra arrived, and the two young scientists were soon immersed in stimulating scientific discussions. Struve had been considering Chandra for the third appointment; now Kuper bombarded him with letters of praise for his young Indian colleague. They convinced the Yerkes director that Chandra was the right choice.

Struve invited him to Williams Bay for a few days in March 1936 after his lectures at Harvard had ended. Chandra went, gave two talks to the astronomers on his research, and impressed them, especially Struve who offered him the job and took him to Chicago to meet the appropriate administrators. Chandra was strongly tempted, but did not accept at first. He returned to Harvard and prepared to go back to England. Hutchins was greatly attracted by the idea of having the Indian astrophysicist on his faculty. Although the President had not been able to see Chandra while he was briefly at Chicago, he sent a radiogram to him on the ship carrying him back to Liverpool. This tipped the scales and Chandra agreed to return to Yerkes in December 1936.

Chandra joined the University of Chicago, Yerkes Observatory as Assistant Professor of Theoretical Astrophysics. He was made an Associate Professor in 1941 and Professor in 1943. At Yerkes, Chandra continued his theoretical research on stellar interiors, but gradually tapered it off as he turned to stellar dynamics, radiative transfer and stellar atmospheres, which he had begun working on at Cambridge. He wrote his first research monograph. "*An Introduction to the Theory of Stellar Structure*," published by the University of Chicago Press in 1939.

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All of Chandra's research depended on his great mathematical powers, the ability to see his way through complicated systems of intergrodifferential equations and solve them. It required immense concentration, self confidence, insight and hard work, all of which he gave in abundance. Many of his papers required massive numerical computations in the days before high speed digital computers; in his early years he did all the computations himself, using electric powered mechanical calculators. His graduate students did some of the calculations and then he had an assistant to do these.

In 1946, Chandra became a Distinguished Service Professor at the young age of 36. In 1944, he was elected to the Fellowship of the Royal Society of London. In 1947 he was awarded the Adams Prize of Cambridge University. In 1952 he was awarded the Bruce Medal of the Astronomical Society of the Pacific. While giving the medal the President of the Society, Professor Otto Struve, remarked that the society has honoured many astronomers in giving this medal but only twice has the society been honoured by giving the awards to such young astronomers (Arthur Stanley Eddington and Subramanyan Chandrasekhar). He has received numerous awards, medals and honours.

CHANDRA - THE TEACHER

The author joined the University of Chicago as a graduate student in January 1955. In the winter quarter the mathematical physics course was taught by Chandra. The author had registered for the course. Chandra would teach on Thursdays (9.30-11.00 a.m.) and Fridays (8.00-9.30 a.m.) every week. He had this programme as he was staying at the Yerkes Observatory campus of the University at Williams Bay which is about 100 miles from Chicago. He was a great teacher who would go into the subtle details of the subject and also point out the excitements. The author still remembers his teaching the Factorization method (due to Leopold Infeld) for the solution of second order differential equations. This method is not to be found in most of the text books. Chandra also introduced his students to the beauty of the variational methods. Of course they had to work very hard to keep pace with his lectures. This happened to be true of any course as the teachers go at a fast pace so as to cover the entire course.

Chandra gave various courses during these days to graduate students (January 1955-June 1958). He gave courses on Quantum Mechanics, Electrodynamics and Optics, Relativity, Stability Problems and Plasma Physics. He mentioned that the reason for giving the course on Electrodynamics and Optics was that he had not taught this course for a long time and he thought he should refresh himself with the subject once again. In this course he described the classical method of taking into account the polorization of light using Stokes parametres. On looking through the note books again, the author finds that in his homework assignment, he had given such elegant problems as

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(i) Show that two beams of oppositely polorized light cannot interfere.

(ii) There is perfect interference only if the beams are similarly polorized.

In Quantum Mechanics course Chandra discussed the variational methods for the solution of Schrodinger equation. He gave a lengthy description of the application of the variational method to the calculation of the binding energy of the H-minus ion. This was clearly not a text book problem and the whole discussion seemed quite complicated to the class which was not aware of the fact that H-minus had a great interest in astrophysics as the principal source of opacity in the outer layers of the sum.

In the Autumn Quarter 1957, Chandra gave a course on Plasma Physics on the campus. In this course he discussed the basic equations and conservation laws, first order orbit theory, adiabatic invariants and their applications which included the stability of the pinch, plasma oscillations and transport phenomena. This was one of the first courses given on the subject after Plasma Physics research had been declassified just around that time. Chandra discussed the various topics in great detail in nineteen lectures of one and half hour duration each. There was lot of interest in the course which was attended by about 20 students. After the course was over, quite a few persons were very regretful that they did not know that Chandra was giving this course. A couple of scientists from Argonne National Laboratory asked the author if they could borrow his notes of Chandra's lectures. The author agreed on the condition that he should get those notes back. It is in order to mention here that there were no xerox or thermofax facilites those days. The author got his notes back.

One of the persons remarked to Chandra that it would help the scientific community greatly if he published his lecture notes in plasma physics on the same pattern as Fermi's notes on Nuclear Physics were published by the UOC press. Chandra asked the author if he would like to undertake this job. The author was not sure in the first instance as it is a very difficult job for a beginer (He had just completed his PhD) to write down the lectures (for print) of a master without making many mistakes. The author finally agreed and Chandra made it clear that he will not go through the manuscript. On one of the return trips to Williams Bay, Chandra told that he had signed the contract with the UOC Press for the publication of the lecture notes and he should have the manuscript ready in a reasonable time; he also told that the royalty on the book will be paid to the author; very gracious of him indeed. The book was published about June 1960 and again as "Midway Reprint" in 1975. It was very well received for at least fifteen years from the date of its publication.

Chandra was staying at Williams Bay. He would come to Chicago every Thursday and usually go back the next day when he was teaching a course in the Physics Department. He would drive down from Williams Bay starting quite early, about 6.00 am.

Some research associates and students took a ride with him to the campus; of course one had to be punctual to the dot because of his very tight schedule. Thursday was a very busy day in the Physics Department at UOC; for Chandra it was busier as he had to go to the UOC Press in connection with the *Astrophysical Journal*, meeting some faculty members, one and a half hour lecture, the faculty seminar, the department tea at 3.30 pm followed by the weekly colloqium. Chandra would stay for Thursday night either at the Quadrangle Club (Faculty Club) or at the International House.

As a student the author was staying at the International House. Chandra would stay there sometime and the two would come across each other in the dining hall or in the lift. The author would greet him very respectfully as one would to a professor of great standing; he was always very cordial and warm. A couple of times he invited the author to his room in the International House and enquired about the various persons in Indian science. Of course, he knew most of them personally—quite a few of them were his contemporaries. The author was really moved by his keen interest in the Indian science and was amazed to note that beneath a very strict and hardworking professor one could feel the great genius, humility and warmth of such a leading scientist.

The author cleared his candidacy examination in June 1956 securing second position in a batch of six students (qualified out of 17) who took the test. The result was declared on a Thursday and it so happened that the author was sitting next to Chandra in the International House cafetaria. Chandra congratulated the author very warmly saying "I hear you have done very well in the candidacy examination". The author then joined him at the dinner table and he asked about his (author's) plans. He suggested that magnetohydrodynamics was an emerging field and it would be quite exciting to work in that field. The author felt most gratified by his suggestion and requested him to accept the author as a graduate student. He asked the author if he had any constraints in regard to time to finish his thesis. The author told Chandra that he was on Government of India scholarship which was to expire in December 1957 and after that he would need financial assistance. The author was told that that would be no problem. He would like him to move to Williams Bay so that he can supervise his work properly. The author agreed to that. It was a privilege to work under his guidance for the next two years. It was a great experience and one learnt so many things from Chandra as one got to know him more. Besides he would drive down to Chicago every Thursday and some of the students and research associates would take a ride with him. On the way he would be discussing some problem or narrating some happening. His knowledge of scientific events, the great men (personal acquaintance with a large number the world over) and history was almost unimaginable.

He was a strict disciplinarian and would be extremely careful in writing the mathematical equations (in long hand) in his manuscripts. On getting the proofs of one of his papers, he found that the typesetter had split some of his equations. He gave a note that the equations be restored to the set up in the manuscript as he had measured the same with a ruler and knew that they would fit in one line. This was done. He was very particular in the style of writing a scientific paper and emphasized that equations are parts of sentences and must be punctuated accordingly. He would also guide as to how to make graphs properly.

Always impeccably dressed in well-tailored suits whose colour vary between dark charcoal and dark grey during the fall and winter and between light grey and tan during summer, and a white shirt, Chandra cut a handsome dignified figure. A word about his white shirt. Once he had to appear on the TV (in 1957) on some programme of the University of Chicago. During the preliminary meeting with the person looking after the programme, she suggested that while appearing on the TV it is better to wear a pastel shade shirt. Chandra asked her what were pastel shades. She remarked any light shade will do. Chandra said he did not have any coloured shirt. The lady was shocked and said" you do not have a single coloured shirt" Chandra replied in the affirmative. The lady was somewhat amused and asked him his shirt size and said she would get him one. In the evening on way back to Yerkes, Chandra narrated with delight this incident and was happy about the gift.

In June 1958 the author graduated, spent three months at Yerkes as a research associate with Chandra and left there in September 1958 to spend a year at Berkley as a research associate with Professor KM Watson. While leaving, the author expressed his deep sense of gratituted to Chandra for all he achieved. He said "Well Trehan I did not do anything for you. You made good use of the opportunities which came your way". He also remarked" when you go back to India, you will face several problems. Do not feel distressed. Ask yourself the question: if you were working on a problem which you thought might get you a Nobel Prize, would these problems be still in your way". The author has tried to follow the advice of his Guruji. It is difficult to state how successful the author has been; however he thinks, he has not been a failure.

THE THEORY OF WHITE DWARFS

The white dwarf stars differ from the normal stars in two fundamental respects. First they are highly "underluminous", that is judged with reference to an average star of the same mass, the white dwarf is much fainter. A typical white dwarf is the companion of Sirius which has a mass about equal to that of the sun but whose luminosity is only 0.003 times that of the sun (i.e. 0.3 percent). Second the white dwarfs are characterized by exceedingly high values of the mean density. The companion of sirius which has mass about equal to that of the sun has a radius of approximately 20,000 kilometers, astonishingly small for such a great mass. This implies a density of 61,000 gms per cubic centimeter or just about a ton per cubic inch. It is the second characteristic which is generally emphasized, though from a theoretical point of view the fact that the luminosity is very small and is of equal importance.

Since the radius of a white dwarf is very much smaller than that of a star on the main series, it follows that for a given effective temperature, the white dwarf will be much fainter than a star on the main series. Similarly for the same luminosity the white dwarf will be characterized by a very much higher effective temperature (i.e. much whiter) than the main series stars. This explains the origin of the term white dwarf.

In 1930, when Chandra was only 19, on the long voyage from India to England, he worked out the theory of white dwarf stars, basing his calculations on Einstein's special theory of relativity and the new quantum mechanics. He obtained the result that if the mass of the star exceeded a certain critical mass, expressible in terms of the fundamental atomic constants, the star would not become a white dwarf.

For sufficiently large M, special relativity comes in eventually and quantum mechanical pressure cannot compete with gravity nor with the classical thermal pressure. In this limit a star will keep on contracting as it radiates away energy and (unless it loses mass first) will eventually suffer a fate worse than death-invisibility. General relativity had preceded quantum mechanics and it was already known that no radiation could escape from a star if it contracted to less than its Schwarzschild radius. Such a state of invisibility is what we now a days call a black hole.

The appreciation of the importance of this discovery by the astronomers was withheld because when Chandra presented his results at the January 1935 meeting of the Royal Astronomical Society in London, Sir Arthur Stanley Eddington began to ridicule the whole idea before the scientific community. He made it look as though Chandra understood neither relativity nor quantum mechanics. More than twenty years passed before the Chandrasekhar Limit became an established fact and assumed its important role in astrophysical research. It is, perhaps in order to mention here the great authority of Eddington, who was the greatest astronomer of his time and what dogmas can do in science.

It took nearly three decades before the full significance of the discovery was recognized and the Chandrasekhar Limit entered the standard lexicon of physics and astrophysics. Five decades passed before he was awarded the Nobel Prize. Chandra remarks" It is quite an astonishing fact that someone like Eddington could have such an incredible authority which everyone believed in and there were not people who had boldness enough and understanding enough to come out and say Eddington was wrong. I don't think in the entire astronomical literature you will find a single sentence to say

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Eddington was wrong. Not only that, I don't think it is an accident that no astronomical medal I have received mentioned my work on white dwarfs.........". He further remarks "I personally believe that the whole development of astronomy, of theoretical astronomy particularly with regard to the evolution of stars, and the understanding of the observations relating to white dwarfs, were all delayed by at least two generations because of Eddington's authority".

Chandra's first research monograph *"An Introduction to the Study of Stellar Structure"* was published by the University of Chicago Press in 1939 and later as Dover edition in 1957 as an unabridged re-publication of the first edition. One of the few treatises in its field, it presents a rigorous examination, using both classical and modern mathematical methods of the relationship between the loss of energy, the mass and the radius of stars in a steady state. Keeping in view the time when the book was published, this was the only monograph where the laws of thermodynamics are presented following Caratheodory's axiomatic standpoint. Chandra writes "The reasons for including this chapter are two fold: first there exists no treatise in English which gives Caratheodory's theory; and second, in the writer's view Caratheodory's theory is not merely an alternative, but elegant approach to thermodynamics but is the only physically correct approach to the second law. Incidentally, the logical rigor and the beauty of Caratheodory's theory may be regarded as an example of the standard of perfection which should be demanded eventually of any physical theory, including the theory of Stellar Structure".

The book then discusses the adiabatic and the polytropic laws and the virial theorem. It represents the work of great pioneers, Ritter, Emden and Kelvin, perhaps, the most important contribution which stellar structure has made to applied mathematics. As Schwarzschild has said the theory of polytropes is a beautiful example of the flowering of a complete mathematical theory of a physical problem. This'is followed by the formal theory of radiation and the equations of equilibrium; gaseous stars, Stromgren's interpretation of the Hertzsprung-Russel diagram; the theory of stellar envelopes as a starter for the theory of gaseous stars, Gibbs statistical mechanics, the theory of degeneracy, the structure of white dwarf stars and stellar energy.

The entire monograph was nearly based upon his own papers or extension thereof. It contained a full discussion of white dwarf stars, including the latest observational results bearing on their masses, radii, luminosities and surface temperatures by Kuiper. There was also a fair amount of material on the hydrogen, helium, and heavy element abundances in stars, derived from their observed physical parameters, for which Chandra had drawn on many discussions with Stromgren.

STELLAR DYNAMICS

Due to this episode, Chandra gave up the studies in Stellar Structure and turned to studies in Stellar Dynamics during 1938-42. He established that a star must experience dynamical friction i.e. it must suffer from a systematic tendency to be decelerated in the direction of its motion. This dynamical friction which the stars experience is one of the direct consequences of the fluctuating force acting on a star due to the varying complexion of the near neighbours. From considerations of a very general nature, Chandra concluded that the coefficient of dynamical friction must be of the order of the reciprocal of the time of relaxation of the system. Among the comprehensive methods of attack on the problems of Stellar Dynamics, mention must be made of the statistical theory of stellar encounters developed by Chandrasekhar and Von Neumann. This statistical theory made fresh start on a variety of problems along which the theory of Stellar Dynamics evolved.

STOCHASTIC PROBLEMS IN PHYSICS AND ASTRONOMY

Chandrasekhar was successful in giving a mathematically rigorous account of the problem of Random Flights first posed by Karl Pearson in 1905. His formulation was as follows: A man starts from a point 0 and walks 1 meter in a straight line; he then turns through any angle whatever and walks another 1 meter in a second straight line. He repeats this process in times. Chandra obtained the solution based on probabilistic arguments. Chandra also gave a very comprehensive account of the theory of Brownian Motion.

These problems were comprehensively discussed in a long article in *Reviews of Modern Physics, "Stochastic Problems in Physics and Astronomy"* (Volume 15, No. 1, 1943, 1-89). This is one of the most widely referred-to and influential articles in this general subject area.

In late 1941, Chandra spent one quarter at the Institute for Advanced Study at Princeton, doing joint research on complex statistical mechanical problems with John Von Neumann. They were both very powerful applied mathematicians, and as Von Neumann was one of the top theorists at Aberdeen (and in several other weapons program as well) they continued their collaboration all during the war years. Chandra was amazingly productive and by 1946 was widely recognised as the outstanding young theoretical astrophysicist in the United States. He was teaching all the theoretical astrophysics courses at Yerkes Observatory and five graduate students had completed their PhD thesis under his supervision.

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RADIATIVE TRANSFER (1943-49)

In the forties Chandra examined the problems of specifying the radiation field in an atmosphere which scatters light in accordance with well defined physical laws. Though this problem originated in the investigations of Lord Rayleigh in 1871 on the illumination and polarization of the sunlit sky, the fundamental equations governing Rayleigh's particular problem had to wait for seventy five years for their formulation and solution. The subject of radiative transfer was given impetus by the work of Schuster in 1905 who formulated the radiative transfer problem in an attempt to explain the appearance of absorption and emission lines in stellar spectra, and Karl Schwarzschild introduced in 1906 the concept of radiative equilibrium in stellar atmospheres.

Radiative transfer provides the foundation for the analysis of stellar atmospheres, planetary illumination and sky radiation. The fundamental problems of the subject are formulated and analysed. It is shown how allowance can be made for the polarization of the radiation field by using a set of parameters first introduced by Stokes. The successive chapters deal with transfer problems in semi-infinite and related astrophysical and mathematical problems.

On the physical side, the novelty of the methods used consists in the employment of certain general principles of invariance which on the mathematical side leads to the systematic use of non-linear integral equations and the development of the theory of a special class of such equations, which can be solved in terms of what are now commonly known as "Chandrasekhar's X and Y functions.

Chandra enjoyed his preoccupation with radiation transfer and, as he often says, it was the happiest period of his scientific life (though he felt the same in later years about his work on the mathematical theory of Black Holes). "My research on radiative transfer gave me the most satisfaction, "says Chandra. "I worked on it for five years, and the subject, I felt, developed on its own initiative and momentum. Problems arose one by one, each more complex and difficult than the previous one, and they were solved. The whole subject attained an elegance and a beauty which I do not find to the same degree in any of my other work. And when I finally wrote the book Radiative Transfer, I left the area entirely. Although I could think of several problems, I did not want to spoil the coherence and beauty of the subject [by further additions]. Further more as the subject had developed, I also had developed. It gave me for the first time a degree of self assurance and confidence in my scientific work because here was a situation where I was not looking for problems. The subject, not easy by any standards, seemed to evolve on its own". The work on Radiative Transfer provided

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(i) to the mathematician some novel problems in integral equations.

(ii) to the astronomer a comprehensive theory of stellar atmospheres.

(iii) to the physicist

- (a) Classical treatment of the polarization of light. This had been done the first time by George Stokes and forgotten. Chandra introduced these to the physicists again.
- (b) An account of neutron transport and diffusion-because the mathematical problems are equivalent.

STABILITY AND TURBULENCE (1952-60)

This period was devoted to a study of hydrodynamic and hydromagnetic stability and the theory of turbulence. These studies were also confirmed experimentally in various cases at a special laboratory set up for the purpose at the University of Chicago. The stability problems were formulated very comprehensively using variational principles. These studies were compiled in the book *"Hydrodynamic and Hydromagnetic Stability"* by S Chandrasekhar (Oxford at the Clarendon Press 1961).

This is a voluminous book (XIX + 654 pages) where Chandra starts with the discussion of the classical Benard Convection problem, then generalises it to include the effect of rotation of magnetic field and then their combined effect. The problems of thermal stability in fluid spheres and spherical shells is then discussed. This is followed by the stability of couette flow and more general flows between co-axial cylinders. The problems of Rayleigh-Taylor and Kelvin Helmholtz instability are then discussed in great depth. The last chapters are devoted to a detailed study of the stability of Jets and Cylinders and some problems of gravitational stability. It has been a great resource book for persons who undertook studies in Magnetohydrodynamic stability in the sixties and later. The work on hydrodynamic and hydromagnetic stability provided:

(i) to the astronomers basis for theories of convection, magnetic fields etc.,

(ii) to the physicst the remarkable achievement that the theories (Some of them at least) had been verified experimentally (at the University of Chicago) to an accuracy of within one percent.

It is indeed one of the strangest ironies in science that Eddington failed to see the far reaching consequences of a very simple and straightforward application of the special theory of relativity while he was amongst the very few to embrace Einstein's general theory in the English speaking world. If Eddington had been open minded about the ideas of relativistic degeneracy and therefore the mass limit, he could have persued the subject in the framework of the general theory and would have possibly found that stars become unstable before they reached the limit and that a black hole would ensue.

Chandra says "Eddington could have done it when I say he could have done it. I am not just speculating. It was entirely within his ability, entirely within the philosophy which underlines his work on internal constitution of stars". It could be said that Chandra's work on black holes was one of his scientific objectives. Having predicted them from astrophysical considerations before anybody else, he had been learning relativity all these years. And gradually from the post-Newtonian approximations to the stability of rotating stars, it was natural for him to move on to the perturbations of black holes. In fact it was his interest (in the sixties) in the ellipsoidal figures of equilibrium and his determination that this theory of Riemann, Jacobi, MacLaurin and Dedekind should be completed and presented in a unified treatment, that postponed for several years his entry into the realm of relativistic black holes. The work was done from 1974 to 1980, culminating in the writing of his book in 1980-81.

From the late 1960's on, Chandra was working seriously on general relativistic problems. By then it was clear that stars more massive than the Chandrasekhar limit that had exhausted their nuclear fuel could contract to much denser neutron stars, which have a similar but larger mass limit, and that still more massive stars could contract to black holes, if they did not explode completely as supernovae. Thus Eddington's question had been answered and Chandra, with his post doctoral research fellows and PhD students, was working out many of the estoric properties of black holes of all masses.

Chandra devoted about nine years to the study of the mathematical theory of black holes. Chandra says (cf: *Chicago Tribute* Oct. 20, 1983) "My latest work represents my best efforts. I spent nine years of sustained effort developing the mathematical theory of black holes, which was recently published in a book of the same name. I consider that my most important work".

ON THE SHOULDER OF GAINTS

Newton's Principia was published in 1687; not only is it the crowning achievement of the 17th century scientific revolution but it is also generally regarded as the most important book in the history of physical sciences. No one can call it an easy read. The first edition ran to only 500 copies. In Newton's own life time only a handful of talented men, working without distraction at the frontiers of current research, had each in his own way achieved a working knowledge of the Principia's technical content. Even in 1730, Voltaire described the book as incomprehensible and obscure. Chandra goes on to say that he regards the Principia as not only surpassed but only unsurpassable. To Chandrasekhar, Newton was not merely a chip off the old block, but the block itself.

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It Newton's Principia for the common reader, Chandra makes considerable effort to circumvent Newton's propensity for a secretive style. Chandra transforms the Newtonian Mathematics into modern idioms and thus makes it much more accessible to what he quainlty refers to as the common reader. This is not to imply universal readership; people will need at least the equivalent of a mathematics degree to understand the proofs.

Chandra arranges the proofs in a linear sequence of equations and arguments. The beauty, clarity, and economy of Newton's achievements shine through. Chandra's personal reflections are more enlightening. He spices his book with a running sequence of introductions and commentaries that reveal both an incisive understanding of the way in which Newton's mind worked and also the pleasure that comes from studying and interpreting Newton's greatest book.

In his lecture on Principia at Pune (IUCAA) in December 1992, Chandra stated that he was asked to give a lecture on Newton's 300th anniversary at Chicago. He had the choice of going through the various books written on Newton or going through the Principia which contain about 450 theorems and then proofs. Chandra thought it more advisable to read the Principia. He said he would write down the theorem and work out the proofs himself. After completing the proofs he said "I was rather ashamed of the fact that in every case Newton's proof was superior to mine". This is in the light of the fact that even to day, there will be very few persons who can absorb the Principia, what to say proving each result independently.

The great joy of Chandra's book is that it repays all the attention one gives to it. As one proceeds, every thing becomes so much easy to understand. The veil of newtonian obscurity is lifted and one begins to grasp the extent of Newton's achievement.

CHANDRA AS MANAGING EDITOR OF THE *ASTROPHYSICAL JOURNAL*

Chandra was the Managing Editor of the *Astrophysical Journal* for almost twenty years (1952-1971). *Ap. J.* was essentially a private journal of the University of Chicago. Chandra played a decisive role in transforming it into national journal of the American Society. It published 950 pages in the year 1952 and 12,000 pages in 1970. The journal improved in quality under Chandra's leadership to become the leading astrophysics journal in the world. "It was a kind of Golden Age for all of us," Says Eugene Parker. "Many of us at times, had difficulties publishing papers in *Ap. J.*, but it was the Golden Age compared to other times and other journals". The final decision to publish a paper or not was entirely Chandra's. He was not immodest, but only truthful, when he wrote to Herman Bondi "The policies of the *Ap. J.* are my policies". This authoritarian rule did not go unopposed. Threats of impeachment ensued, but by and large there was universal acclaim of his stewardship to which he responds:

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"A journal is what the authors write. The editor does not solicit articles; the articles come to him. If the editor has in some way encouraged publication of good papers, promptly, efficiently, and fairly, he has done a little service but the credit for the quality is not the editor's. It belongs to the astronomical community".

Chandra worked very hard as Editor of the *Astrophysical Journal*, and it prospered under his management. The cold war and then the post-sputnik era converted science, space and astrophysics into growth subjects, and he presided over an almost 15 fold increase in the number of pages published from 1952 until 1971, when he gave up the reins of the Journal to Helmut Abt.

CHANDRA AT ABERDEEN

During World War II, Chandra, still a British subject, worked as a half time consultant at the Ballistics Laboratory of the Aberdeen Proving Ground in Maryland. He alternated three weeks there, working on shock waves, dense gases, and radiation in explosions, and then three weeks back at Yerkes Observatory doing research in theoretical astrophysics. Sadly, in rural Maryland Chandra encountered racial prejudice from ignorant Proving Ground Gaurds, just as he had in Chicago where the Dean of Physical Sciences, Henry G Gale, did not want a person with a dark skin on the campus. The Dean made it clear that he would not accept him there. In 1940, Gale retired and his succssor, Arthur H Compton, was quite the opposite; he admired Chandra, whom he remembered meeting on a scientific visit to India. Under Compton and later Deans, Chandra was always welcome on the campus of Chicago.

THE NOBEL PRIZE

The announcement, October 20, 1983, by the Royal Swedish Academy of Sciences said "Subramanyan Chandrasekhar, of the University of Chicago, and William H Fowler, of the California Institute of Technology, won the Physics Prize for their discoveries about the birth, evolution and death of stars. Many scientists have studied these problems but Chandrasekhar and Fowler are the most prominent".

Chandrasekhar said "The award appears related to my work on the maximum mass of white dwarf stars which I discovered in 1930 while on a steamer enroute from India to England". Chandrasekhar published his theory despite opposition from colleagues. Years later, astronomers not only confirmed the existence of white dwarfs but found they are among the most common stars in the cosmos.

Fowler remarked "I am very pleased, just astounded to be awarded the prize with Dr. Chandrasekhar. His work covers the gamut. I can see his getting the prize, but my own work has been restricted to a rather narrow, but important, part of the field".

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The Nobel committee said that although both men did much of their pioneering work decades ago, their discoveries have "gained renewed interest, because of the great progress of astronomy and space research in recent years".

The Chicago Tribune, dated Thursday, October 20, 1983 writes "Speaking in his apartment in Chicago's Hyde Park with his wife Lalitha at his side, Chandrasekhar said: "I work for my own personal satisfaction on things generally outside the scientific mainstream. My work has become appreciated only after some period of time".

"The Nobel Laureate said he considers his later work on black holes more important. "My latest work represents my best efforts, "he said. "I spent nine years of sustained effort developing the mathematical theory of black holes, which was recently published in a book of the same name. I consider that my most important work.

The reporter continues "In Chicago, Chandrasekhar refused to characterize his work for reporters. "I do not do experiments. It is very difficult to describe my work" he said. "It is very theoretical. It is very difficult to make a capsule statement and I wouldn't want to try".

Colleagues of Chandrasekhar said he is intensely shy and extremely hardwoking, yet warm and sensitivie, especially to his students. The University of Chicago President, Hanna Gray said "Our entire community will celebrate the award of the Nobel Prize to Subramanyan. No one better fulfils the mission of our University. He is a scientist without peer, a teacher of teachers and a devoted, selfless and humane participant in all our creativity, the divine spark in mankind, writing about it, but most of all embodying it".

The Chicago Tribune concludes with the remarks that Chandrasekhar has been the recipient of 12 honorary degrees and has been admitted to the membership of 18 learned societies. He is the 52nd Nobel Prize winner who has either taught or studied at the University of Chicago.

Years later, in 1983, while much was being said publicly and privately among the circle of his students, colleagues and admirers about the fifty year slumber of the Nobel committee in belatedly awarding him the prize for his white dwarf work, Chandra remained light hearted and could say that he was happy that this most prestigious prize came after all the other prizes and awards. Otherwise, he says, his story would have been like that of a certain general in the army who attended a dinner with rows and rows of pins and medals on his well starched uniform. When a lady at the table asked him in awe and admiration, what all those honours stood for, the general pointed to the top medal and said "Dear lady, this one, this top one was awarded to me by mistake. The others followed as a domino effect".

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CHANDRA AND LITERATURE

Chandra had a deep and abiding interest in literature and classical music. He cultivated them with the same degree of thoroughness and intensity as his science. "My interest in literature began in a serious way in Cambridge about 1932" says Chandra "I used to devote most of the two to three weeks between terms to the study of literature. The real discovery for me at that time was the Russian authors. I read systematically, in Constance Garnett's translation, all the novels of Turgenev, Dostoevski's Crime and Punishment, Brothers Karamazov and Possessed. Chekhov, I read of course all his stories and plays. Not all of the Tolstoy's but Anna Kareina certainly. Among English writers I started reading Virgina Woolf, TS Eliot, Thomas Hardy, John Galsworthy and Bernard Shaw. Henrik Ibsen was also one of my favourite authors. The only serious literary study I have accomplished since I came to the United States is that of Shakespeare's plays. I have read all of his plays at least once, and some, especially the tragedies, I have read three or four times".

He gave the second Ryerson Lecture at the University of Chicago in 1975. The tilte "Shakespeare, Newton & Beethoven or the patterns of creativity." In this lecture the main point was why it is that in the arts and literature, the quality of work improves with age and experience while in science, generally it does not. Chandra felt that we do science in isolation, focus narrowly on our immediate goals and that we are not sufficiently broad in our interests and persuits. He feels that one would do better science if one read Shakespeare, particularly his penultimate play, The Tempest".

With such a wide background of achievements in science, Chandra presents two contrasting images to those around him. To those who have had no close association with him, his most ascethtic, highly disciplined, organised and simplified life makes him seem completely unapproachable, someone to be respected from a safe distance. For instance a student once told him "Most people think you are an orgre". But those who have worked with him closely or made an effort to know him have a different experience altogether. "He is so intense in all his interests" says James Cronin (a Nobel Laureate)" that one gets the impression that he is averse to small talk. He is not. He is a man full of warmth and friendship with deep human concern".

"There is a kind of fineness about him "says Marvin Goldberger", both from a physical and from a philosophical point of view. He is one of the most elegant looking people I have ever met". Victor Weisskopf first met Chandra when he was a Cambridge graduate student spending a year in Neils Bohr Institute in Copenhagen in 1932. "The strange thing about Chandra is that he has changed very little. He has got white hair, but apart from that he looks to me exactly like he looked at that time. Right from the beginning, but even more later on, he became sort of the most pure example of the ideal

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scholar in Physics.... nothing of deep education, his humanistic kind of approach to these problems, his knowledge of world literature and in particular English literature are outstanding. I mean you would hardly find another physicist or astronomer who is so deeply civilized".

PROFESSOR EMERITUS

Chandra obtained the status of Emeritus Professor in 1986 by terminating his indefinite appointment with the University of Chicago because "it is better to leave when every body asks 'why are you leaving?' than to stay while everybody wonders when is this guy thinking of retiring?'

Chandra has been active in science from 1928-1995, a span of 68 years, produced about 50 PhD's, published about 400 papers, 11 books and seven volumes of selected papers. He was Managing Editor of *Astrophysical Journal* for almost two decades. Very few scientists have accomplished this. He covers almost four generations. A small fraction of it would have satisfied a lesser mortal. Chandra's knowledge of the history of scientific events was also quite fabulous. He was, perhaps, one of the very few links which provided connection with scientists of three or four generations. One could hear from him the great events in science and about the scientists from 1930 onwards - personal reminiscences of Bohr, Rutherford, Dirac, Heisenberg, Eddington and others. Let me conclude this with the "concluding remarks of his Nobel Lecture (1983).

"The simple is the seal of the true
and Beauty is the splendour of truth".

SK TREHAN
146, Sector 9/B
Chandigarh-160 009

Honours, Medals and Prizes awarded to S Chandrasekhar

1934 Fellow, Indian Academy of Sciences Bangalore.

1944 Fellow of the Royal Society of London.

1947 Adams Prize (Cambridge University)

1952 Broce Medal (Astronomical Society of the Pacific)

1953 Gold Medal (Royal Astronomical Society)

1955 Member, National Academy of Sciences, USA

1957 Rumford Medal (American Academy of Arts & Science)

1962 Fellow, Indian National Science Academy.

1962 Royal Medal of the Royal Society of London.

1966 National Medal of Science (USA).

1968 Padma Vibhushan (INDIA).

1971 Henry Draper Medal (National Academy of Science, (USA).

1973 Smoluchowski Medal (Polish Physical Society).

1974 Dannie Heinman Prize (American Physical Society).

1983 Nobel Prize for Physics (Royal Swedish Academy).

1984 Dr Tomalla Prize (ETH, Zurich).

1984 Copley Medal of the Royal Society of London.

1984 RD Birla Memorial Award (Indian Physics Association)

1985 Vainu Bappu Memorial Award (INSA).

Books by S Chandrasekhar

1. An Introduction to the Study of Stellar Structure. Chicago : University of Chicago Press 1939. Repr. New York : Dover 1958, 1967 Translations in Japanese & Russian.
2. Principles of Stellar Dynamics. Chicago : University of Chicago Press 1942 Repr. New York : Dover 1960 Translated into Russian.
3. Radiative Transfer Oxford : Clarendon Press 1950. Repr. New York : Dover 1960. Translated into Russian.
4. Plasma Physics : Notes compiled by SK Trehan from a course given by S Chandrasekhar at the University of Chicago, Chicago : University of Chicago Press 1960, 1975.
5. Hydrodynamic and Hydromagnetic Stability: Oxford: Clarendon Press 1961. Repr. New York: Dover 1970, 1981. Translated into Russian.
6. Ellipsoidal Figures of Equilibrium. New Haven : Yale University Press 1969 Repr. New York: Dover, 1987 translated to Russian.
7. The Mathematical Theory of Black Holes, Oxford: Clarendon Press 1983.
8. Eddington : The most distinguished Astrophysicist of his time, Cambridge : Cambridge University Press 1983.
9. Truth & Beauty : Aesthetics and Motivations in Science, Chicago, University of Chicago Press 1987.
10. Newton's Principia for the Common Reader, Oxford Clarendon Press, 1995.
11. Selected Papers : The University of Chicago Press :

    Volume 1 : Stellar Structure and Stellar Atmospheres. 1989, (516 pages).

    Volume 2 : Radiative Transfer and Negative Ion of Hydrogen, 1989, (622 pages).

    Volume 3 : Stochastic, Statistical and Hydromagnetic Problems in Physics and Astronomy, 1989 (642 pages).

    Volume 4 : Plasma Physics, Hydrodynamic and Hydromagnetic Stability and Applications of the Tensor—Virial Theorem, 1989, (586 pages).

    Volume 5 : Relativistic Astrophysics, 1990, (588 pages).

    Volume 6 : The Mathematical Theory of Black Holes and of colliding Plane Waves, 1991, (740 pages).

    Volume 7 : The Non-Radial Oscillations of Stars in General Relativity and other writings, 1997, (295 pages)