S Chandrasekhar: His Life and Science

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1. Introduction

Subramanyan Chandrasekhar (or 'Chandra' as he was generally known) was born at Lahore, the capital of the Punjab Province, in undivided India (and now in Pakistan) on 19th October, 1910. He was a nephew of Sir C V Raman, who was the first Asian to get a science Nobel Prize in Physics in 1930. Chandra also went on to win the Nobel Prize in Physics in 1983 for his early work "theoretical studies of physical processes of importance to the structure and evolution of the stars". Chandra discovered that there is a maximum mass limit, now called 'Chandrasekhar limit', for the white dwarf stars around 1.4 times the solar mass. This work was started during his sea voyage from Madras on his way to Cambridge (1930) and carried out to completion during his Cambridge period (1930–1937). This early work of Chandra had revolutionary consequences for the understanding of the evolution of stars which were not palatable to the leading astronomers, such as Eddington or Milne. As a result of controversy with Eddington, Chandra decided to shift base to Yerkes in 1937 and quit the field of stellar structure.

Chandra's work in the US was in a different mode than his initial work on white dwarf stars and other stellar-structure work, which was on the frontier of the field with Chandra as a discoverer. In the US, Chandra's work was in the mode of a 'scholar' who systematically explores a given field. As Chandra has said: "There is a complementarity between a systematic way of working and being on the frontier. To be systematic and to develop a subject to a certain completion requires that the subject is capable of being so treated. You cannot do that if the subject is something which is just beginning." At Yerkes he successively worked in the field of stellar dynamics (1938–43), radiative transfer (1943–50), and after systematically exploring each field and bringing it to a certain state of completion, Chandra would summarize his understanding of the field as an authoritative monograph. After 1952 he was associated more with the Physics Department of the University of Chicago, but the pattern continued to be the same with the successive areas, hydrodynamic and hydromagnetic stability (1953–61) and ellipsoidal figures of equilibrium (1961–68). Chandra started getting attracted to the General Theory of Relativity in the early sixties and worked successively in

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relativistic astrophysics (1962–71), black holes (1974–83) and later in colliding gravitational waves and space-time singularities during the last phase (1983–1995) of his life.

A reflective component also developed in Chandra's life after 1975 leading to his beautiful writings on the problems of beauty and motivation in scientific life and on Newtonian *Principia.* Chandra also devoted a large amount of his time to teaching (guiding some 45 PhD students) and to his editorship of *The Astrophysical Journal* which he brought to international standards.

2. Early Days at Lahore and Madras (1910–1930)

Chandra was the eldest son and the third child of his father Chandrasekhar Subramanya Iyer and his wife Sitalakshmi in a family of four brothers and six sisters. Being the eldest son he inherited the name Chandrasekhar from his grandfather Ramanathan Chandrasekhar (RC), who was the first to make a move from a village life, centered on agriculture, to a life of intellect and to get an English education. He was caught up by the real spirit of education and read whatever his fancy dictated including literature, philosophy and even mathematics and physics on his own. He was also a connoisseur of Carnatic music. He became a lecturer in mathematics, physics and physical geography. His independence of spirit in pursuing knowledge for its own sake and his extensive collection of books laid the foundation of a family which produced a large number of scientists over many generations of which his second son C V Raman and the grandson Chandra are the most distinguished.

Figure 1. S Chandrasekhar.

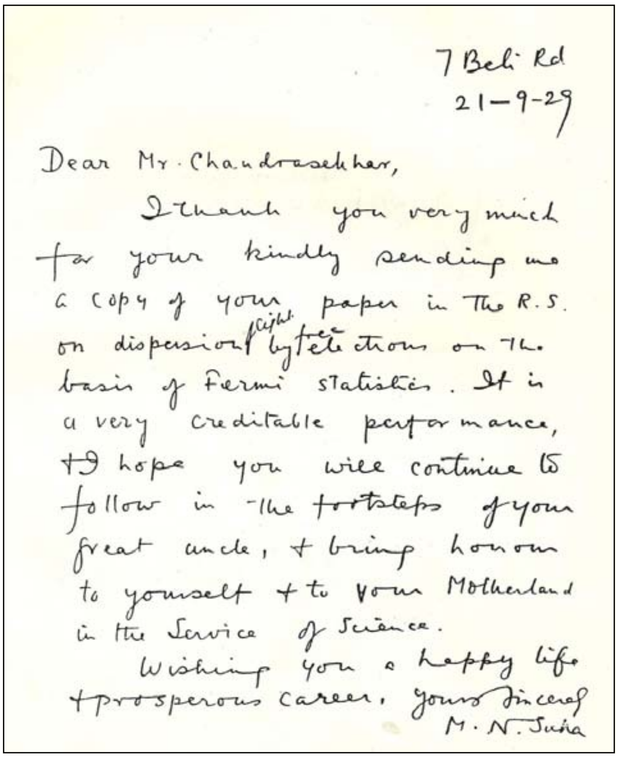
Figure 2. Chandra with his uncle Sir C V Raman. Reproduced with permission from *C.V.Raman – A Pictorial Biography* compiled by S Ramaseshan and C Ramachandra Rao, IASc, Bangalore, 1988.

Figure 3. Prof. S Chandrasekhar at the function to unveil Ramanujan's bust at the premises of Indian Academy of Sciences, Bangalore, 1985.

Chandra's father C S Iyer, the eldest son of RC, was a brilliant student and joined government service (Indian Audit and Accounts Service) in 1907 at Calcutta. The job involved postings at various places in India and in 1910 while he was posted at Lahore as the deputy auditor general of the North-Western Railways that Chandra was born. His mother Sitalakshmi was the daughter of Diwan Bahadur Balakrishnan. As Chandra says "My mother, ... was a woman of high intellectual attainment (she translated into Tamil, for example, Henrik Ibsen's *A Doll's House*), was passionately devoted to her children, and was intensely ambitious for them." It was her pointing out to ten-year old Chandra the example of Srinivasa Ramanujan, Indian mathematician, and his extraordinary achievements that Ramanujan became a perennial source of inspiration for Chandra to pursue a research career.

Following a pattern established in the family, Chandra's early education was at home. His father was transferred to Madras (now Chennai) in 1918 where he decided to build a large house, '*Chandra Vilas*' for his constantly increasing family to provide it a permanent base. After school education at the Hindu High School, Triplicane in Madras, Chandra joined the Presidency College for his university education and completed BSc (Hons.) from there in June 1930. Initially he had wanted to do BSc (Hons.) in mathematics, a subject in which, of course, he was very good. Besides, he was under the spell of Ramanujan and wanted to follow his example. His father, however, who was quite authoritarian, wanted him to prepare for the Indian Civil Service (ICS) examination which led to highly lucrative and prestigious positions in government service. Chandra's heart was, however, set upon a career of research in science. He had the example of his uncle, C V Raman, who had given up just such an administrative career for a life of research in physics. As a result of all these pressures on him, Chandra ended doing his BSc (Hons.) in physics.

In February 1928 C V Raman, along with K S Krishnan, discovered Raman effect at Calcutta. Chandra spent the summer months at his uncle Raman's laboratory, discussing the underlying theoretical physics of Raman's work with them. Soon after coming back to Madras, Chandra learnt of an upcoming visit of Sommerfeld to India. Among other places, Sommerfeld's itinerary included the Presidency College, Madras. This was rather exciting. Chandra had already read Sommerfeld's book *Atomic Structure and Spectral Lines.* This book from whose successive editions, four in all, everybody in those days learned old quantum theory of Planck, Bohr and other pioneers, was the bible for modern atomic physicists in those days. Chandra looked forward eagerly to meet the great man. Meeting Sommerfeld was a shocking experience for Chandra. Sommerfeld announced that his book had now become outdated, as the old quantum theory had been replaced by new discoveries in Quantum Mechanics by Schrödinger, Heisenberg and Dirac. Even Maxwell–Boltzmann statistics had undergone a change, being replaced by quantum versions of the statistics. Chandra was naturally upset. Sommerfeld left with him, however, copies and galley proofs of his papers discussing applications of Fermi–Dirac statistics to his electron theory of metals, and Chandra says "from which even an undergraduate student (as I was then) could learn". Chandra regarded this meeting as the "*single most important*" event of his life. He soon mastered these papers and embarked on original research while studying for his undergraduate degree. Immediately thereafter, he applied Fermi–Dirac statistics to the problem of Compton scattering and felt that the results deserved publication in the *Proceedings of the Royal Society* of London. Such papers, however, had to be communicated by a Fellow of the Royal Society. While searching for an appropriate person to communicate his paper, Chandra came across the name of Ralph Fowler, FRS, who had published his theory of white dwarf stars applying the new statistics to them in the *Proceedings.* This was another fateful encounter for Chandra. Ralph Fowler agreed to get Chandra's paper published and it appeared in the *Proceedings* in 1929. Incidentally, this was not Chandra's first paper which happened to be 'Thermodynamics of Compton effect with reference to the interior of the stars', published in *Indian Journal of Physics* in 1928. Soon, there followed two more papers on the new statistics in the *Philosophical Magazine* in 1930. In this period he also had the opportunity of showing Heisenberg around Madras during his visit. He was getting recognized in Indian circles as a promising young scientist. Saha wrote him a letter of appreciation on receiving a copy of the *Royal Society* paper. His college principal Philip Fyson managed to get a special Government of India Fellowship created for Chandra so that he could proceed to UK for higher studies. Chandra officially learnt about



7 Beli Rd
21-9-29

Dear Mr. Chandrasekhar,

I thank you very much for your kindly sending me a copy of your paper in the R.S. on dispersion of light by electrons on the basis of Fermi statistics. It is a very creditable performance, & I hope you will continue to follow in the footsteps of your great uncle, & bring honour to yourself & to your Motherland in the Service of Science.

Wishing you a happy life & prosperous career. Yours sincerely
M. N. Saha

Figure 4. Meghnad Saha's letter to Chandra.
Credit: Prof. Virendra Singh

it on 22 May 1930. Chandra decided to go to Cambridge and study under Ralph Fowler. The final decision to do so was however not so easy and was even painful. His mother, to whom he was deeply attached, had been sick since 1928 and it was not clear that he would ever see her again if he went to England. But his mother, Sitalakshmi, herself insisted that Chandra should avail of this opportunity. Chandra sailed for Venice on the steamship Pilsna, of the Lloyd Triestino fleet, from Bombay Harbour on 31 July 1930.

3. Cambridge Period (1930–1937)

3.1 *White Dwarf Stars and Chandrasekhar Limit*

Eddington, whom Chandra has called the founder of modern astrophysics had published his magisterial work *The Internal Combustion of Stars* in 1926 summarizing his work of the previous ten years in the field. The book gave us our present understanding of the problem for all, but the superdense stars. However, it was known that there were superdense white dwarf stars, e.g., the companion of Sirius, which have densities of the order of $10^5 - 10^6$ gms/cc. For these there was a problem. As Eddington says "I was uneasy as to what would ultimately happen to these superdense stars. The star seems to have got itself into an awkward fix. Ultimately its store of subatomic energy would give out and the star will want to cool down. But could it? The enormous density was made possible by the high temperature which shattered the atoms. If the material cooled, it would presumably return to terrestrial density. But that means that the star must expand to say 5000 times its present bulk. But the expansion requires energy – doing work against gravity; and the star appeared to have no store of energy available. What on earth was the star to do if it was continuously losing heat, but had not the energy to get cold!"

It was Ralph Fowler who in 1926 rescued the superdense stars from this dilemma. For this purpose he made use of the new Fermi–Dirac statistics to the degenerate high density electron gas instead of classical Maxwell–Boltzmann statistics leading to Boyle's law. As we have seen, Chandra became aware of Fowler's work in 1929. He then extended Fowler's work by using the more realistic polytropic gas spheres to the Fermi–Dirac equation of state for the electron gas. The main results obtained were

$$MR^3\mu^5 = 2.14 \times 10^{28},$$

and

$$\rho = 2.162M^2,$$

where M is the mass (in units of the solar mass), R is the radius, μ is the mean molecular weight and ρ is the mean density of the white dwarf star. Besides, the central density was estimated to be about six times the mean density. Thus all superdense stars can happily end their career as white dwarf stars. Chandra had finished this paper before leaving for the UK.

The sea voyages used to be leisurely affairs in those days. Chandra carried with him three books on this long journey as study and reference material. These were (i) Compton's *X-Rays and Electrons*, (ii) Sommerfeld's *Atomic Structure and Spectral Lines* and (iii) Eddington's *The Internal Constitution of Stars*. During the voyage Chandra started to wonder about relativistic effects in the white dwarf stars. In Fowler's and his own work, so far, electrons had been treated as non-relativistic particles. For large electron number densities (greater than 6×10^{29} per cm^3) we need to use the relativistic form of the Fermi–Dirac statistics. Sommerfeld had discovered fine structures of hydrogen spectral lines by a similar consideration of relativistic effects. Chandra probably expected similar corrections in his investigation. What Chandra found however was, not some perturbation correction, but rather a drastic change. It turned out that the relativistic effects lead to an upper limit $M_{\rm Ch}$ for the mass of the white dwarf stars. To quote from Chandra's later calculation, based on his 1935 paper, we have

$$M_{\rm Ch} = 0.197 \left[\left(\frac{hc}{G} \right)^{3/2} \frac{1}{m_{\rm H}^2} \right] \frac{1}{\mu_{\rm e}^2} M_\odot \,,$$

where $\mu_{\rm e}$ is the mean molecular weight per electron, $M_\odot$ is the Solar mass and $m_{\rm H}$ is the mass of the hydrogen atom. h, c and G are the usual fundamental constants: $h =$ Planck's constant, $c =$ velocity of light and $G =$ Newton's gravitation constant. Numerically, we get

$$M_{\rm Ch} = 1.44 \left(\frac{2}{\mu_{\rm e}} \right)^2 M_\odot \,.$$

Note that the presently acceptable value is $\mu_{\rm e} = 2$, unlike $\mu_{\rm e} = 2.5$ which was current at the time Chandra wrote the note. The existence of Chandrasekhar Limit for white dwarf stars was a revolutionary conclusion. It restored the problem about which Eddington was worried. How would heavier mass stars end their life?

Chandra hoped to discuss the content of these two papers with Fowler after he landed in England. He arrived in London on 19 August 1930 and had to face annoying bureaucratic hurdles in getting admitted to Cambridge and this took even longer as Fowler was away. They finally met on 2nd October 1930. Fowler made Chandra feel welcome. He was quite enthusiastic about Chandra's Indian paper and he later communicated it to the *Philosophical Magazine*. About Chandra's revolutionary shipboard paper, he was not so sure and wanted to consult E A Milne.

Chandra was convinced of the correctness of his results on the limits on white dwarf mass. However, finding that both Fowler and Milne were not quite convinced and were not willing to communicate it to the *Royal Society*, he sent a small note, of two published pages, to the *Astrophysical Journal* in the USA, where it was published.

3.2 *Distorted Polytropes*

Chandra, besides taking courses from Fowler, Eddington and Dirac in physics and some mathematics courses, continued to do research on relativistic and stellar atmospheres. In these he was encouraged by Milne and even began collaborating with him. He was elected to Sheep Shank's Exhibition, with an award of forty pounds, of Trinity College in recognition of his research work. This was also followed by an invitation to meet Eddington on 23 May 1931 together with a note of congratulations.

Chandra received a devastating telegram on 21 May 1931, informing him of his mother's passing away. Chandra was consumed with grief and to escape Cambridge he spent the summer in Göttingen with Max Born.

At the suggestion of Dirac who was supervising Chandra when Fowler was away on a sabbatical, he spent most of his third year of fellowship at Bohr's Institute at Copenhagen. Besides, he had a private agenda to explore in the new atmosphere – a shift to theoretical physics from astrophysics. The attempt was abortive. Since he had to finish his PhD thesis before his current fellowship expired in August 1933, he worked on the equilibrium of star polytropes distorted by rotation, by tidal forces, in a double-star system, and by combined rotation-tidal effects. His polytrope work was well appreciated by Milne, Russel and Eddington. For this work Chandra received his PhD in 1933. Not only that, he also received a Fellowship of Trinity College for three years. This removed the uncertainty about his future research career. Besides, it was a rare honour and rather gratifying for Chandra to have received a fellowship which had been held earlier by his idol, mathematician Ramanujan, the only Indian to do so before him. He held this fellowship until 1937.

3.3 *Controversy with Eddington*

Milne, around 1930, was getting interested in the problem of stellar structure. His point of departure was the assumption that all stars must have a degenerate matter core surrounded by matter behaving as a perfect gas. In Eddington's earlier investigations entire star matter obeyed perfect gas laws and as he put it: "*it would be absurd for me to pretend that Professor Milne has the remotest chance of being right*".

Chandra thought that the Eddingtion–Milne controversy, for both of whom he had great regard, could be resolved by using the exact equation of state of the matter following from quantum statistics, purely as a scientific problem. Such a calculation would take into account the variation of the pressure-density relation in different parts of the star. So Chandra decided to pursue these detailed calculations. He submitted two papers regarding these results of his investigation in 1934 to *Royal Astronomical Society.* He accepted the invitation to present a brief talk on his results at the forthcoming January 1935 meeting.

Chandra and Eddington were, by this time, almost in daily contact about their research, yet Eddington somehow did not tell Chandra that he was also going to speak at this meeting. In fact, when they did meet each other a day before the meeting, Eddington told Chandra that he had asked the organizers to give Chandra half an hour, instead of fifteen minutes, to present his results and Chandra thanked him for that. Chandra had just learnt, a little bit before this meeting, that Eddington was also going to speak on 'Relativistic Degeneracy' there but Eddington did not breathe a word about it, making Chandra apprehensive.

At the meeting, after Chandra's presentation, Eddington spoke. He was a powerful speaker and represented the astronomy establishment. He hit out at Chandra's results and declared that "*there is no such thing as a relativistic degeneracy*" but only non-relativistic degeneracy, which he referred to as "ordinary degeneracy". It is not that he detected any mathematical error in Chandra's calculations. What he could not and would not accept was the consequence for the ultimate fate of massive stars following from Chandra's discovery. As Eddington emphasized: "*The star has to go on radiating and radiating and contracting until, I suppose, it gets to a few km radius, when gravity becomes strong enough to hold in the radiation and the star can at last find peace.*" Here, Eddington came close to discovering the black hole final state for very massive stars but he recoiled from drawing that conclusion. As he continued "*I felt driven to the conclusion that this was almost a reductio ad absurdum of the relativistic degeneracy formula. Various accidents may intervene to save a star, but I want more protection than that. I think there should be a law of Nature to prevent a star from behaving in this absurd way.*"

Why was Eddington so averse to what Chandra's discovery was leading to for the fate of the massive stars? As has been emphasized by Freeman Dyson, the astronomers, since the days of Aristotle, were believers in a perfect peaceful heavens. The present paradigm of a 'violent universe' with which all our popular astronomy is replete now was unthinkable for them. Chandra's work introduced a revolutionary change in this Aristotelian universe where, for gravitationally dominated stars, no equilibrium was possible.

Eddington, even though he had nothing more than his strong feeling about the absurdity of behavior of the star, if Chandra's work were to be accepted, went on to doubt Chandra's use of relativistic quantum mechanics. As he says "*The* *formula is based on a combination of relativistic mechanics and non-relativistic quantum theory, and I do not regard the offspring of such a union as born in lawful wedlock.*" This, however, was not correct. Even worse, he went on to heap ridicule on Chandra by referring to some confusion he had on the use of progressive versus stationary waves in quantum mechanics. The general impression on the audience was that the great Eddington had demolished Chandra's work and it suffered from error of both principle and calculations. The effect on Chandra can well be imagined.

A word about what Chandra's work implied for Milne's model may be appropriate here. Chandra's work also showed that, in view of the Chandrasekhar limit, the degenerate core mass has an upper bound. Further, in more massive stars, in view of the important role played by radiation pressure, such domains of degeneracy cannot develop. Milne also did not accept these conclusions as they went against his model. Milne was more inclined to doubt the correctness of Quantum Mechanics. As he said "your marshalling of authorities such as Bohr, Pauli, Fowler, Wilson, etc., very impressive as it is, leaves me cold". Incidentally, the quantum mechanics community, with the exception of C Möller, were also not inclined to contradict astronomy stalwarts such as Eddington and Milne in print, though they agreed with the correctness of Chandra privately.

Surprising as it may seem, Chandra and Eddington stayed good friends despite their controversy, though this controversy had a great effect on the career trajectory and style of Chandra's work and on the progress of astrophysics. He and Milne also remained good friends. He gave the 'Milne Lecture' at the Oxford University on 6 December 1979 on the scientific work of his friend. Chandra was also invited to deliver two centenary lectures on Eddington on 19 and 21 December 1983 at the Trinity College of Cambridge and he chose the title 'Eddington: The Most Distinguished Astrophysicist of His Time'.

Faced with the apathy of stalwarts like Eddington and Milne and the astronomical community, Chandra decided to quit further research on white dwarf stars. As he wrote to his father in 1940, "I foresaw for myself some thirty to forty years of scientific work and I simply did not think it was productive to constantly harp on something which was done. It was much better for me to change the field of interest and go to something else." He continues with the hope "If I was right, then it would be known as right. For myself, I was positive that a fact of such clear significance for evolution of stars would in time be established or disproved. I did not see a need to stay there, so I just left it."

Chandra has asked the basic question in his conclusions to his 1932 *Zeitschrift für Physik* paper, and these are very much quoted lines, as follows:

"We may conclude that great progress in the analysis of stellar structure is not possible before we can answer the following fundamental question: *Given an enclosure containing electrons and atomic nuclei,* (*total charge zero*) *what happens if we go on compressing the material indefinitely*?"

Of course, the answer was not known in those days but if Chandra's work had been accepted, the progress in their exploration would have come earlier and accepted much earlier. It turned out that, like white dwarf stars, there is also another final state, viz., 'neutron stars', but that is also possible for stars up to a maximum of 2 to 3 solar mass. The answer for really massive stars was worked out by Oppenheimer and Snyder in their paper 'On continued gravitation contraction' in 1939. This was also somewhat ignored.

It took a long time, about 30 years, for Chandra's work to get generally accepted and enter physics and astronomy mainstream. Though he received many awards from the astronomy community, the first award to cite the white dwarf work was Dannie Heinemen Prize, awarded by the American Physical Society in 1974. The Nobel Prize, also for this early work of Chandra, would come only in 1983.

4. Yerkes Observatory

As his Trinity fellowship was coming to an end, he accepted an offer made by Otto Struve of a research associateship at the Yerkes Observatory of the University of Chicago at William Bay, Wisconsin from January 1, 1937. He also had an offer from Harvard University. Shortly before arriving in the US, Chandra made a short trip to India to visit his family after a long absence of six years and to marry Lalitha Doraiswamy. Chandra had known Lalitha at the Presidency College, Madras, where she had also been studying and was now the Headmistress of a school. She had been waiting for him as they felt committed to each other and were married on 11 September 1936. Chandra arrived at Yerkes with his wife Lalitha in December 1936.

Yerkes had emerged as a major astronomical observatory under the Directorship of Struve, who was now planning to make it a strong centre for theoretical astronomy as well. His offer to Chandra, Kuiper and Strömgren was part of that effort. As Martin Schwartzchild says: "Yerkes became a leading institution in every respect including the development of one of the most outstanding, if not the most outstanding, graduate schools in astronomy and astrophysics in the country. Chandra was by far the most active member of the group. He just loved to give lectures and was very demanding of his students, many of whom felt enormous loyalty to him."

4.1 *Stellar Structure*

As we have noted before, Chandra had decided to quit the field of stellar structure. He decided to present a completed account of the field as he saw it and completed his book *An Introduction to the Study of the Stellar Structure* which appeared in 1939. Some of his research papers deal with the proofs of the results to be presented in the book. In the last but one chapter, he dealt with his work on relativistic degeneracy and devoted just a few footnotes to his controversy with Eddington. After Eddington's classic book, Chandra had produced a classic text on the subject. After writing this book, he only carried out a few more investigations on the subject. The most important among them is the 'Schönberg–Chandrasekhar Limit' which gives the maximum mass of a non-degenerate core in a star.

4.2 *The Scholarly Phase*

Chandra's decision to quit the field of stellar structure as a consequence of his controversy with Eddington and wrapping up that phase of life in the form of an authoritative text started a new pattern of work in his life, which one may call the 'Scholarly Phase', in which Chandra would choose a new area of research and then work on it, almost exclusively, until he was satisfied that he had understood the field to his satisfaction and then move on to another field after summarizing his understanding in the form of a classic text. Unlike in the Cambridge days, where he worked like a normal astrophysicist, on a topic of current interest, he would not be swayed in this phase by what was fashionable but only by what he felt needed to be understood. To quote from Chandra's autobiography at the time of the Nobel award, "There have been seven such periods in my life. These phases are:

(i) stellar structure, including the theory of white dwarf stars (1929–1939),

(ii) stellar dynamics, including the theory of Brownian motion (1938–1943),

(iii) the theory of radiative transfer, including the theory of stellar atmosphere and the theory of negative ion of the hydrogen atom, and, the theory of planetary atmospheres including the theory of illumination and polarization of the sunlit sky (1943–1950),

(iv) hydrodynamic and hydromagnetic stability, including the theory of Rayleigh–Bénard convection (1952–1961),

(v) the equilibrium and the stability of the ellipsoidal figures of equilibrium, partly in collaboration with Norman R. Lebovitz (1961–1968),

(vi) the general theory of relativity and relativistic astrophysics (1962–1971), and

(vii) the mathematical theory of black holes (1974–1983)."

As per the pattern, there were monographs resulting from each of these periods summarizing the subject which would then serve as a base for all future work in these areas except for the period (vi).

4.3 *Second Period*: *Stellar Dynamics* (1938–1943)

Chandra's next field of venture was stellar dynamics. The main problem here is to understand the equilibrium velocity distribution of the stars in the galaxies. Also important is to understand the approach to equilibrium of such a system.

4.3.1 *The Ellipsoidal Hypothesis*: Chandra's first paper in the *Astrophysical Journal*, containing 154 pages with eight parts, dealt with the distribution function $f(\vec{r}, \vec{v}, t)$ with stellar coordinates $\vec{r}$ and velocity $\vec{v}$ at time t for the steady-state cases. The time-dependent cases were handled in the second paper, of 202 pages in six parts, in the same journal. The function f was taken to obey collisionless Boltzmann equation. The simplifying assumption was the ellipsoidal hypothesis, i.e., f depends on the velocities only through the combination

$$(u \cdot M \cdot u + \sigma) \ ,$$

where $u = v - v_0(\vec{x}, t), M = M(\vec{x}, t)$ is a symmetric matrix, $v_0(\vec{x}, t)$ = mean star streaming velocity at the position $\vec{x}$ at time t, $\sigma = \sigma(\vec{x}, t)$ is a scalar function. The system leads to ten coupled partial differential equations, together with a number of integrability conditions and other connecting equations. It was not possible to solve these equations in all generality despite Chandra's valiant efforts. He obtained a complete solution for the two-dimensional case with circular symmetry for the non-steady case.

4.3.2 *Fluctuations of Gravitational Field in a Stellar System*: As a first approximation, it is appropriate, as was shown by Jeans, to consider each star moving in the average gravitational field of all the other stars at its position. In the next approximation of the calculation of star orbits, it is necessary to take into account the deviation of the actual distribution from the averaged out star distribution. This entails a calculation of the time average of $\Sigma(\Delta E)^2$, where ΔE is the energy change a star undergoes in a binary collision with another star. Because of the long range nature of gravitation, this quantity is rather tricky to estimate, as calculations involve infinities. The calculations, earlier to Chandra, by Eddington, Karl Schwartzchild and Rosseland had also been incorrect. He wrote a series of papers dealing with the relaxation time of star systems such as a globular cluster of stars or those in the Milky Way galaxy.

At this stage Chandra wrote his monograph on stellar dynamics, which appeared in 1942. As it happened, he should have waited somewhat longer. The best was yet to come. In a paper 'A statistical theory of stellar encounter' Chandra initiated a better approach. In two papers, in collaboration with John Von Neumann, he was able to give more rigorous shape to these ideas. In these papers they also worked on the speed of gravitational fluctuations. The most important contribution of Chandra was his discovery of 'dynamical friction', published in 1943. This arises as a result of deceleration arising from the long-time averaging of the gravitational field fluctuations on the motion of a star. Like friction, the deceleration is proportional to the velocity of the star and is in the direction of motion. The dynamical friction was used to estimate the rate of escape of stars from galactic clusters or the time required for the galactic clusters to evaporate. The effect of the dynamical friction substantially increases the evaporation times of the clusters by a factor of between 15 to 50 depending on its central density. When a Dover reprint of his monograph on stellar dynamics appeared in 1960, his papers on dynamical friction and some other work were included in it.

His studies of Brownian motion in physics and astronomy also date from this period. A review paper 'Stochastic Problems in Physics and Astronomy' which appeared in the *Reviews of Modern Physics* in 1943, has been an evergreen favourite with the scientists and has the largest citation among all his papers. In this he also discussed the statistics of gravitational fields due to some random distribution of stars.

Chandra was elected to Fellowship of the Royal Society of London in 1944. His name was proposed by C V Raman, seconded by E A Milne and supported by Fowler, Jeans, Eddington, Whittaker, Harold Jeffreys and others. Chandra, incidentally, first learnt of his nomination from Milne, and not from Raman, who also informed him that Eddington was particularly keen that he should be elected that year. Chandra also became a full Professor at the University of Chicago in 1944, within two years of his having become Associate Professor there in 1942.

4.4 *Third Period*: *Radiative Transfer and H^- Atom* (1943–1950)

4.4.1 *Radiative Transfer*: Chandra next shifted his interest to the problems involving radiative transfer. Between 1944–1948, he wrote a series of 24 papers with the title 'On the Radiative Equilibrium of a Stellar Atmosphere' in the *Astrophysical Journal*, which revived the field. The complexity arises because the scattering of radiation by each layer of the atmosphere causes the source function to depend on the radiation leading to complicated integro-differential equations for the radiative transfer. There may also be reflection of radiation and diffuse transmission in the atmosphere.

Chandra summarized his results in the monograph *Radiative Transfer* in 1950. As Chandra said in the preface of this monograph, "In this book I have attempted to present the subject of radiative transfer in plane parallel atmospheres as a branch of mathematical physics with its own characteristic methods and techniques. On the physical side, the novelty of the methods consists in the employment of certain general principles of invariance, which, on the mathematical side, leads to the systematic use of nonlinear equations and the development of the theory of a special class of such equations. On these accounts the subject would seem to have an interest which is beyond that of the specialist alone: at any rate that has been my justification for writing this book. However, my own partiality has led me to include two chapters which are probably of interest only to the astrophysicist."

Three main contributions which Chandra made to the field are as follows.

(i) *The Discrete Ordinate Method*: Chandra used extensively, a method earlier used by Wick, to reduce his integro-differential equations to an approximate, finite set of ordinary differential equations. This was done by a quadrature scheme, e.g., Gaussian quadrature formula for integrals, to reduce them to discrete summation. It is now referred to as Wick–Chandrasekhar discrete ordinate method. That these approximation methods converge was also shown later.

(ii) *Invariance Principles*: Chandra became aware of the work of Ambartsumian, done in 1943–1944, only in the summer of 1945 and later. Ambartsumian had introduced the use of invariance principles in the problems involving radiative transfer. He was impressed by the power of these methods to elucidate the nature of the solution to these complex problems. Chandra wrote a beautiful personal account of this for the 40th anniversary of the Principle of Invariance symposium held at Byurakan, Armenia, in 1981. The first of the two invariance principles of Ambartsumian, as he stated them, is

" I. *The law of diffuse reflection by a semi-infinite plane-parallel atmosphere must be invariant to the addition (or subtraction) of layers of arbitrary thickness to (or from) the atmosphere.*"

The second invariance principle refers to the case of "*diffuse reflection and transmission by a plane-parallel atmosphere of a finite optical thickness*".

As Chandra says "... Ambartsumian's principles needed generalization to the case when the intensity is represented by the Stoke's vector and scattering is governed by a phase matrix instead of a phase function. And finally it appeared that Ambartsumian's principle could be formulated not so much in the sense of expressing invariance as of grasping the essential mathematical content of the geometrical scaffolding of the physical description that is sought". Chandra formulated his four "invariance principles" which he saw as "manifest consequence of the *definitions* of the scattering and transmission functions."

(iii) *Polarization*: Chandra's work was motivated by the desire to give a theory of polarization of the sunlit sky. The previous work by Lord Rayleigh was based on the assumption that it is adequate to consider a single scattering of radiation by the atmosphere. While many general features of the polarization of the sunlit sky could be accounted for this way, it was inadequate to account for many finer features. For example, that the polarization of sunlit sky vanishes sometimes at two or three points of Sun's meridian circle (known as Babinet, Brewster, and Arago points) depending on the Sun's position, was not accounted for by Rayleigh's theory. Chandra was successful in giving a proper and complete account of the polarization of the sunlit sky.

Chandra was very happy with his work on radiative transfer. As he said "My research on radiative transfer gave me the most satisfaction. 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 in any of my other work." He further adds, "It gave me for the first time a degree of self assurance and confidence on 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."

4.4.2 *The Negative Ion of Hydrogen*: The problem of opacity of the atmosphere of cooler stars was a puzzle for quite some time as the known sources of common metals, only partly ionized and the neutral hydrogen atoms could not give an account of it. In 1938 Rupert Wildt attributed the discrepancy to photo-absorption by the negative ions of hydrogen and provided a solution to this puzzle. These ions are formed by combination of free electrons, provided by metallic ionization, with the neutral hydrogen. Chandra carried out necessary calculations of sufficient accuracy, as the negative ion of hydrogen is only marginally bound, on the necessary absorption coefficients and binding energy of the ion and used them to explain solar opacity.

4.4.3 *Aberdeen Proving Grounds*: Chandra had a more than full load of teaching at Yerkes while he was doing all this extensive work in the radiative transfer and other research problems. Not only that, due to demands of scientific work for the second world war, he was, at the invitation of John von Neumann, spending only half the time at Yerkes and the other half at Aberdeen Proving Grounds (APG) – three weeks at a time – where he was involved in the problems of ballistics, shock waves, neutron diffusion, etc. He did this from February 1943 to the end of the war. Incidentally, the mathematical techniques used in his work on radiative transfer have been of great value in neutron diffusion studies as well.

On the negative side it should be noted that at APG Chandra was exposed to racial discrimination problems as Aberdeen was a rural area. He isolated Lalitha from these by not taking her to APG.

Chandra was cleared for work at Los Alamos in September 1944 but decided not to join as he felt that the war was coming to an end.

5. After the Second World War

5.1 *The Princeton Offer*

The universities in the US devoted themselves to rebuild their war depleted departments soon after the second world war was over. Chandra received an offer from the Princeton University to succeed Henry Norris Russel at twice his current salary of $5000 at Yerkes. Chandra was prevailed upon not to leave his present position, by Robert Hutchins, the Vice Chancellor of the Chicago University, who offered him a Distinguished Service Professorship that matched the Princeton offer of $10,000. Hutchins also said "One thing that we cannot offer you is the honor of succeeding Russel because we don't have a Russel. However, this honor of succeeding to that position is ill advised. It is far more honorable to leave a professorship to which it is honorable to succeed than to succeed to an honorable position". He emphasized the point by asking Chandra "*Do you know who succeeded Lord Kelvin in his chair at Glasgow which he occupied for fifty years*?" Hutchins was also directly involved in Chandra's initial appointment at Yerkes so as to counter racial prejudice strongly prevalent at that time. He thus became Morton D Hull Distinguished Professor at the University of Chicago in 1946.

5.2 *The Astrophyical Journal* (1952–1971)

Chandra became the managing editor of the *Astrophysical Journal* in 1952 and continued till 1971, a long period of almost two decades. Chandra was responsible for almost all aspects of this journal, along with only a part time secretary for the first twelve years, during this long period. Initially the journal was only a house journal of the Chicago University. He was responsible for converting it into a national journal of the American Astronomical Society and by strictly maintaining the standards of the journal papers, he made it into a leading astronomy journal of the world. He was the ultimate referee of all the papers published there. The journal increased enormously in size from some 950 published pages in 1952 to some 12,000 pages in 1970. He also started *Astrophysical Journal Supplements* series and in 1967 an 'Astrophysical Journal Letters' section. He also brought the journal out of the financial doldrums into one with a reserve fund of $500,000 when he left. Jean Sacks, the Head of the Journals Department, said at his farewell function "I have often come across, in the papers submitted to the A P J the term 'Chandrasekhar Limit'. I do not think there is such a thing as the Chandrasekhar limit."

There were, however, some negative aspects as well. The journal took a lot of Chandra's time. He devoted half of his time to the journal and the other half to teaching and research. The time was strictly partitioned and no cross-activity was allowed. This caused many misunderstandings between him and the contributors. Another source of friction was his strict standard in publishing papers and this made him somewhat aloof from the astronomy community. Many friends, like Fermi, wondered why he kept the burden for so long, which would have been killing for research work for anybody but Chandra?

5.3 *Troubles at Yerkes* (1952)

During the summer of 1952, when B Strömgren was spending time away from Yerkes, Chandra was acting as the Department Chair and he came in conflict with him over administrative matters. Strömgren, during 1952 itself, appointed a committee to overhaul "the curriculum Chandra had designed and taught for the preceding fifteen years". Chandra was not even consulted about the changes. The new curriculum totally downplayed the theoretical astronomy. Chandra felt humiliated. As Chandra said "It became a matter of self respect for me. I had no choice. If the people at Yerkes did not want the kind of science I was doing at the time, I had to find a place in the university where such science could be done." He never resigned from Yerkes though and continued to live there till 1964.

Around this time Fermi asked Chandra to join The Research Institute (now called Enrico Fermi Institute) and the Department of Physics of the University of Chicago. Henceforth he taught at the physics department but almost never at the astronomy department. Chandra said, "This experience in the early 1950's did as much good for my science, if not more than my earlier episode with Eddington, because it made me associate with people like Fermi and Gregor Wentzel, whom I would not have had close contact with if I had stayed at Yerkes. I set up an experimental laboratory in hydromagnetism with Sam Allison. I taught all the standard courses in physics, quantum mechanics, electrodynamics, etc. I was the first one to teach relativity at the University of Chicago, which of course led me to research in relativity."

Chandra was awarded the Bruce Medal in 1952 and the Gold Medal of the Royal Astronomical Society in 1953, the honours which only Eddington had before him by the age of 42. Another landmark change in 1952 was he and Lalitha finally became naturalized US citizens. His father never reconciled himself to this step.

6. At the Department of Physics, University of Chicago

As we have seen, Chandra started teaching at the department of physics from 1952 onwards, and his research underwent a change of direction nearer to physics but still of interest to astrophysics. We will give a brief account of the work done during this period.

6.1 *Fourth Period*: *Hydrodynamics and Magnetohydrodynamics* (1952–1961)

Chandra's work in this field dealt with many topics. We shall discuss only a few of his important contributions here.

6.1.1 ***Linear Stability Problems*:** The phenomenon of thermal convection was discovered by Count Rumford. The convective stability had been studied earlier by H Bénard, Lord Rayleigh and H Jeffreys. Chandra studied with thoroughness the problem of onset of convection in the case of Bénard problem of a fluid, confined between two parallel planes, and heated from underneath. He considered the modification of this problem when rotation and magnetic field were also present, either singly or simultaneously. He also dealt with the problem of thermal instability in spheres and spherical shells. Chandra was awarded the Rumford Medal in 1957 by the American Academy of Arts and Sciences.

Chandra studied the stability of Couette flow of fluid between rotating cylinders and Poiseuille flow with pressure gradients. Complications arising from the conductivity of the fluid and the presence of magnetic field were also included. Further, he investigated the Rayleigh–Taylor instability when two fluids rested on each other, and the Kelvin–Helmholtz instability when the two fluids were in relative motion.

Chandra's monograph *Hydrodynamic and Hydromagnetic Stability* (1961) summarized his work in this field. By dealing with this vast and classic field, in the same clear notation, Chandra rendered the field a great service.

6.1.2 ***Galactic Magnetic Fields*:** Chandra and Enrico Fermi wrote two papers on galactic magnetic fields. In the first of these papers, they estimated the galactic magnetic field, using two different methods, to be about $6 - 7 \times 10^{-6}$ gauss. These are about twice the present day estimates. Such a magnetic field is strong enough to confine the galactic cosmic rays. The second paper was on gravitational instability in the presence of a magnetic field, primarily using the virial theorem.

6.1.3 ***Other Investigations*:** We have not touched on the extensive work of Chandra on turbulence. He also wrote three papers on thermonuclear confinement problem with Kaufmann and Watson. The lecture notes of his course on Plasma Physics was written up by S K Trehan and appeared as a book. Outside this general area, he wrote, with Münch, a series of six papers on fluctuations in the brightness of the Milky Way.

6.2 *Fifth Period*: *Ellipsoidal Figures of Equilibrium* (1961–1968)

Chandra was invited to deliver Sillman Memorial Lectures in 1963 at Yale University. He decided to speak on 'Rotation of Astronomical Bodies'. The subject had been studied and developed by past masters like Newton, Maclaurin and Jacobi. Chandra also studied the later work by Dirichlet, Dedekind, Riemann, Poincaré and Darwin. Despite this, as Chandra says "the subject, nevertheless, had been left in an incomplete state with many gaps and omissions and some plain errors and misconceptions. It seemed a pity that it should be allowed to remain in that destitute state." Chandra published a series of forty papers, mostly in collaboration with Norman R Lebovitz, on the subject to remedy the situation. He wrote a monograph, *Ellipsoidal Figures of Equilibrium* (1969) summarizing his results. He made a powerful use of tensor virial theorem, discovered by him, in these studies.

Chandra was not sure as to how much this effort was worth. But with the discovery of fast pulsars and active galactic nuclei, the work has been found to be of wide use.

Chandra received National Medal of Science, of the United States, in 1966.

7. Shift to General Relativity (1962–1995)

Chandra began to get seriously interested in General Theory of Relativity in early sixties. In preparation, he gave a course on the subject at the University of Chicago in 1961, which was the first ever course on general relativity there. He attended the third international conference on general relativity and gravitation at Warsaw in 1962. He still had a big distraction from it, however, in that he still had to wrap up his work on ellipsoidal figures of equilibrium. Chandra, while addressing the International Astronomical Union, pointed out, "General Theory of Relativity is a theory of gravitation; and like the Newtonian theory of gravitation, which it refines and broadens, its natural home is astronomy." The theory, however, had been ignored by both physicists and astronomers, excepting in Cosmology, for half a century. As Chandra puts it, it had proved to be "a graveyard of many theoretical astronomers". The revival of interest was given an impetus by the discovery of pulsars and quasars in the 1960s. Chandra, however, deserves the credit for bringing the general relativity to its natural home.

7.1 *Sixth Period*: *General Relativity and Relativistic Astrophysics* (1962–1971)

7.1.1 ***Stability of Relativistic Stars*****:** Chandra, in his first foray in the field, decided to deal with the stability of spherical perfect-fluid stars under radial perturbations. In Newtonian theory for the corresponding problem it was found that the star is stable if the adiabatic index for the perfect fluid is greater than 4/3. Chandra found that the general theory of relativity has drastic effect on this result. General relativity led to an upper limit on the density of the star so that it is stable. The later refinement of this argument by J Bardeen, J Hartle, etc., made it into a strong theoretical argument for the existence of black holes.

In further work by Chandra, the assumption of the spherical symmetry was dropped so that one could include the effect of rotation, and, include the effect arising from gravitational radiation and other phenomena arising from lack of symmetry.

7.1.2 *Post-Newtonian Approximation*: Most of the rigorous methods developed by Bondi, Sachs, Penrose and Newman were not directly of use in the astrophysical context. Chandra developed post-Newtonian approximation framework for general relativitistic equations of motion. With Newtonian gravitation results forming its lowest order approximation, a systematic perturbation expansion is developed in powers of the ratio of "matter velocity v to light speed c", i.e., in powers of (v/c). His students Nutku and Esposito were also involved in some of this work. One of the drawbacks of the earlier attempts had been to treat matter as point particles. While this works for the case of electromagnetism, there are problems in using point particle model in gravitational theory due to nonlinear effects. Chandra assumed matter to be compact bodies, treating the outside gravitational field as if the compact body was a point mass.

A difficult problem was to treat the gravitational radiation effects correctly. They appeared in 2 1/2 order post-Newtonian approximation, i.e., in terms of the order of $(v/c)^5$. Chandra, with his systematic approach was able to get it correctly for the first time in a work in collaboration with Esposito. Chandra's results on these gravitational radiation effects found their direct and important use in elucidating such effects in Hulse–Taylor pulsar discovered in 1974.

It should be noted that this post-Newtonian approximation scheme is most likely to be an asymptotic approximation in the weak field and low velocity limit.

Chandra suffered a heart attack in 1974.

7.2 *Seventh Period*: *Black Holes* (1974–1983)

His next area of research activity was in the mathematical theory of black holes. He was deeply fascinated by the elegance of their mathematical expression. As he said, in a famous passage, in 1983, "The black holes of nature are the most perfect macroscopic objects that are there in the universe: the only elements in their construction are our concepts of space and time. Since the general theory of relativity provides only a single unique family of solutions for their description, they are the simplest objects as well."

The unique family of solutions referred to above is the Kerr metric, discovered by Roy Kerr in 1963, which is characterized by two parameters with the significance of mass m and angular momentum a. If the Maxwell field is included along with the Einsteinian gravity, the generalization of Kerr metric is the Kerr–Newman metric which needs one more parameter, viz., total electric charge Q to describe it, apart from m and a. If the angular momentum a vanishes, then the Kerr metric becomes the well-known spherical Schwartzchild metric. Most of Chandra's work is concerned with studying the first order gravitational perturbation on these stationary metrics. Chandra did a comprehensive and elegant job on the perturbation of Schwartzchild, Reissner–Nordstrøm and Kerr metric black holes. In all these cases, he was able to separate the gravitational perturbation equations. Only the Kerr–Newman case defeated him. He could not find a similar separation in this case and nor has anyone else been able to find it so far.

Chandra's separation and decoupling of equations for Maxwell and Dirac fields on a Kerr background spacetime was a tour de force, especially for the case of Dirac field. He derived great pleasure from it. Chandra collected his results in the monograph *The Mathematical Theory of Black Holes* (1983), which became an instant classic.

During the middle of 1977, Chandra also underwent a heart bypass surgery. He was awarded the Nobel Prize in Physics in 1983.

7.3 *Eighth Period*: *Colliding Gravitation Waves* (1983–1995)

Chandra was 73 years of age now and it was not clear to many that Chandra could go on as before in research. In this period Chandra's work was mostly concentrated on colliding gravitational waves. He may have been led to this work by a letter from Y Nutku, who had done doctoral work with him in 1969, who brought to his attention the fact that when two impulsive gravitational waves, having non-parallel polarization collide, the metric is described by the simplest solution of the equation Chandra had come across earlier in his re-derivation of Kerr-metric.

In his first paper with Valerie Ferrari, Chandra analyzed completely the Nutku–

Halil spacetime metric. Later with Xanthopoulos, Chandra extended the analysis by including various kinds of matter. Later papers discussed the issue of space-time singularities arising from the colliding waves. According to Penrose "Colliding plane waves indeed have the habit of leading to such singularities; and there is at least the possibility that these singularities may be closer to being realistic than those which occur in the Schwartzchild black hole (too special symmetry) and the Kerr black hole (closed time-like curves and intervening Cauchy horizon)."

7.4 *The Beginning and The End*

As has been remarked by Penrose, "In a sense, Chandra's lifetime work was like a circle, basically starting with his insights that led us to believe that too massive white dwarfs must collapse to a space-time singularity, and finally reaching back to a sophisticated study of those very singularities."

NASA has named one of its four 'Great Observatories' Chandra X-Ray Observatory which was launched on July 23, 1999.

8. The Reflective Phase (1975–1995)

We have so far discussed mainly the life in research of Chandra with a few biographical notes to put things in context. Chandra's style of research, throughout most of his life in America, was very intensive and comprehensive in his chosen area of research. He carried out thousands of pages of elaborate and complicated algebraic manipulation, and, massive numerical calculations – sometimes with the help from Donna Elbert – for each of his research projects. He also was massively into teaching. He guided some 23 PhDs in astronomy and astrophysics, 21 PhDs in physics and even one PhD in chemistry. He devoted half of his time for nineteen years in editing the *Astrophysics Journal*. This hardly left him any time to pursue his other interests in life, such as literature and music. Also, not much time was left for him to reflect about broader aspects of science. But in his more mature years he did take some time out for it.

8.1 *Aesthetics and Motivations in Science*

Chandra was asked to deliver the second Nora and Edward Ryerson Lecture, given in April 1975, and he decided to do so on the 'Patterns of Creativity' using Shakespeare, Newton and Beethoven as examples of creativity in literature, science and music respectively. A few months before he delivered this lecture, he had a heart attack and Chandra decided to read Shakespeare more thoroughly

Figure 5. Prof. S Chandrasekhar with Smt. M S Subbulakshmi, renowned Carnatic Vocalist, during the Academy Golden Jubilee Celebrations, Bangalore, 1985.

during his period of recovery. The doctors had forbidden him to do science. His lecture is a delight to read besides being an in-depth reflection on creativity. Earlier to this lecture, Chandra had only spoken on such a topic only once, in 1946, on differences between the basic and derived sciences, on the invitation of Robert Hutchins, Chancellor of University of Chicago . Later he came back repeatedly to questions of "aesthetics and motivations in Science". Some of these have been collected in a book *Truth and Beauty* (1987). They are full of deep thoughts and have a literary grace, making one wish that Chandra had written more such pieces.

Chandra was fond of referring to Rayleigh's answer to his son, when the latter quoted Huxley's quip that 'a man past sixty does more harm than good'. "Rayleigh was sixty-seven at that time and his response was: *that may be, if he undertakes to criticize the work of younger men, but I do not see why it should be so if he sticks to things he is conversant with.*" As Chandra concluded "perhaps there is a moral in it for all of us!" This may perhaps explain Chandra's continued creativity throughout his life.

8.2 *Newton's Principia*

Chandra was invited to lecture at the 300th anniversary of *Principia* (1687) of Isaac Newton. Chandra had great respect for this "magisterial" work. He decided to take this opportunity to study it more closely. In order to appreciate the achievements of Newton, Chandra proceeded as follows: "I first constructed for myself, proofs for them (Newton's propositions). Then I compared my proofs with those of Newton. The experience was a sobering one. Each time I was left in sheer wonder at the elegance, the careful arrangement, the imperial style, the incredible originality, and above all the astonishing lightness of Newton's proofs; and each time I felt like a schoolboy admonished by his master."

Chandra also followed another rule of the game in the above venture: to use only mathematical methods available to Newton in those days. The result of this work was a large volume *Newton's Principia for the Common Reader* (1995). This was Chandra's last monograph.

Suggested Reading

A. Biographical

- **[1] K C Wali, *Chandra*: *A Biography of S. Chandrasekhar*, University of Chicago Press, 1991.**
- **[2] *Chandrasekhar*: *The Man Behind the Legend, Chandra Remembered*, Edited by K C Wali, World Scientific, 1997.**
- **[3] *A Scientific Autobiography*: *S Chandrasekhar*, Edited by K C Wali, World Scientific, 2011.**
- **[4] A I Miller, *Empire of the Stars*: *Friendship and Betrayal in the Quest for Black Holes*, Houghton Mifflin Co., Boston, 2005.**

B. Chandra's Science

- **[1] *From White Dwarfs to Black Holes*: The Legacy of S. Chandrasekhar, Edited by G Srinivasan, Univ. Chicago Press, 1997.**

The following obituary notices for Chandra are also to be noted:

- **[2] R J Tayler, *Bio. Memoirs of Fellows of Royal Society*, Vol.42, pp.81–94, 1996. This also contains a complete list of Chandra's publications.**
- **[3] R H Garstang, *Publn. Of Astr. Society of the Pacific*, Vol.109, pp.73–77, 1997.**
- **[4] D Lynden-Bell, *Q J R Astr. Soc*., Vol.37, pp.261–263, 1996.**

The following special issues of scientific journals were devoted to Chandra:

- **[5] *Current Science*, Vol.70, No.9, 10 May 1996.**
- **[6] *Physics Today*, December 2010.**

A popular account of the Chandrasekhar limit appears in the following book:

- **[7] G Venkataraman, *Chandrasekhar and His Limit*, University Press, 1992.**

C. Chandrasekhar's Scientific Writings: Books

- **[1] *An Introduction to the Study of Stellar Structure*, Univ. Chicago Press, 1939; Dover Reprint, 1958, 1967.**
- **[2] *Principles of Stellar Dynamics*, Univ. Chicago Press, 1942; Dover Reprint, 1960.**
- **[3] *Radiative Transfer*, Clarendon Press, Oxford, 1950; Dover Reprint, 1960.**
- **[4] *Plasma Physics*, Notes by S K Trehan, Univ. Chicago Press, 1960; Reprint 1962, 1975.**
- **[5] *Hydrodynamic and Hydromagnetic Stability*, Clarendon Press, Oxford, 1961; Dover Reprint, 1970, 1981.**
- **[6] *Ellipsoidal Figures of Equilibrium*, Yale Univ. Press, 1969; Dover Reprint, 1987.**
- **[7] *The Mathematical Theory of Black Holes*, Clarendon Press, Oxford 1983.**
- **[8] *Eddington*: *The Most Distinguished Astrophysicist of His Time*, Cambridge Press, 1983.**
- **[9] *Truth and Beauty : Aesthetics and Motivations in Science*, Univ. Chicago Press, 1987.**
- **[10] *Classical General Relativity*, Edited by S Chandrasekhar, Oxford Univ. Press, 1993.**

[11] *Newton's Principia for the Common Reader*, Clarendon Press, Oxford, 1995.

[12] *The Theory of Turbulence, Subramanyan Chandrasekhar's 1954 lectures*, Edited by A Spiegel, Springer, 2010.

D. Chandrasekhar's Scientific Writings: Research Papers

A complete list is given with R J Tayler's obituary notes on Chandra. The following seven volumes containing some selected papers were published by the University of Chicago Press.

1–7: Selected Papers (Seven Volumes), 1989–91.

Another selection of Chandra's papers was edited by K C Wali:

8–9: *Quest for perspectives*: *Selected works of S Chandrasekhar* (with commentary), 2 Volumes, World Scientific, 2001.

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