Subrahmanyan Chandrasekhar

R. Nityananda

Subrahmanyan Chandrasekhar, the astrophysicist, died on 21 August 1995 at Chicago, where he had worked at the University for the last fifty-eight years. He would have turned eighty-five on the 19 of October this year. His last book, *Newton's Principia for the Common Reader*, had just been published by the Oxford University Press, the product of his dedicated studies over the last several years. He was in the process of preparing for a lecture and thus died as he always lived – working.

His career can be summarized simply enough – an Honours degree in physics at the Presidency College, Madras (1926–1929), a doctorate (1930–1933) followed by a fellowship (1933–1937) at Cambridge University in England, then a move across the Atlantic to the Astronomy Department at the University of Chicago, which was located at that time at Yerkes Observatory, about a hundred miles from the city. He married his college classmate Lalitha, who survives him, in 1936. His positions at the University started with a research associateship and culminated in the Morton D. Hull Distinguished Service Professorship, which he held from 1952 till he relinquished it in 1986 because 'it is better to leave when everybody asks "Why are you leaving?" than to stay while everybody wonders "When is this guy thinking of retiring?"'.

The list of his scientific contributions makes clear why Chandrasekhar was a legend in his own time. In 1930, fresh from his undergraduate degree, he combined the principles of quantum mechanics and special relativity to calculate the pressure of the electrons in white dwarf stars. The result was dramatic – there was a maximum mass, roughly one-and-a-half times that of the sun, above which a sphere of cold matter sustained only by electron pressure would continuously shrink under gravity, never finding any equilibrium configuration. There were indeed earlier papers which had noticed that these principles imply a maximum mass. A year later, Landau wrote a characteristically brief paper which pointed out the existence of the limit, and went on to speculate, presciently about stars with the density of atomic nuclei, and incorrectly about new physics – energy nonconservation – coming into play. Chandrasekhar's work was distinguished both by mathematical thoroughness and a conviction that the result was of fundamental importance. Strong conviction was badly needed, because Arthur Eddington, the Plumian Professor of Astronomy at the University of Cambridge, ridiculed the final result as an absurdity, claiming that one of the starting assumptions was in error. Since Eddington could not pinpoint the error in a manner acceptable to physicists ('I think there should be a law of nature to prevent the star from behaving in this absurd way'), an impasse resulted which is hard to understand so many years later. The personal relationship between Chandrasekhar and Eddington seems to have continued in spite of these events, and he did spend some years in Cambridge after his doctoral degree, though they could scarcely have been comfortable ones. The astronomy community, at least in the United States, seems to have reacted by accepting Chandrasekhar into its midst, without taking any stand on his remarkable result. His own reaction was probably the most remarkable and ultimately fruitful. He wrote his first book on stellar structure, an exposition of both existing knowledge and his new ideas. The style is so lofty and detached that the reader senses no hint of the skepticism and confusion then prevalent amongst astronomers. With this he bid goodbye to the controversy. The stand he had taken on the existence of a maximum mass – known to everyone else as the 'Chandrasekhar limit' – was ultimately vindicated by subsequent theory and observation. The award of the Nobel Prize of Physics in 1983 was primarily for this work.

At the Golden Jubilee meeting of the Indian Academy of Sciences.

Around the year 1938, he commenced research in a new area, the dynamics of stars moving in clusters and galaxies under their mutual gravitational attraction. The greatest strength of his work on stellar dynamics was the systematic calculation of the effects of 'encounters' between stars in a cluster – not physical collisions but random gravitational scattering by neighbours. He developed a parallel with the theory describing the Brownian motion of a colloidal particle in a fluid. *En passant*, he wrote the standard survey article on the latter subject as well, in the *Reviews of Modern Physics* of 1943. Generations of theoretical physicists, not necessarily interested in stars, have learnt the basics of Brownian motion from this reference. The deepest consequence of this parallel was that, in spite of the apparent randomness of the scatterings, a star must experience a systematic effect tending to bias its velocity to the mean of its neighbours. His name for this effect – dynamical friction – is as much a part of the vocabulary of astrophysics as the Chandrasekhar limit. Such a process is now known to operate not only in clusters of stars but in much larger scale systems as well, e.g. in merging galaxies.

The work on stellar dynamics ended around 1945 – in this one instance he appears to have written his book, which appeared in 1942, before the picture was complete. His grand strategy was now established. Five years of deep study and calculation and a book now followed, devoted to radiative transfer – the mathematics underlying the emission, absorption, and scattering of photons in the atmospheres of stars and the pattern of intensity and polarization which emerges to enter the telescopes of astronomers. Today, the problem in its most general and realistic form is attacked by massive computation. Even Chandrasekhar's book begins with a discussion of numerical integration. But after this prosaic start comes a *tour de force* – the nonlinear integrodifferential equations of the theory admit an exact solution in special cases, at least after persuasion by the master craftsman. This calculation gave him the greatest personal satisfaction, stemming not so much from impact as from its elegance. A fruitful physical idea underlies this achievement. While the outcome of the totality of the scattering process in a finite slab of material is usually complicated, the change in the outcome caused by adding one more thin layer can be expressed in a simpler form. This 'invariant embedding' principle also carries with it the 'principle of invariance'. When the slab is semi-infinite, addition of one more layer must reshuffle the individual photons in direction and polarization but leave the overall pattern of the radiation the same.

Lecturing at the Raman Research Institute

A systematic study and exposition of hydrodynamic and hydromagnetic instability followed in the next decade, and his book on the subject (which has grown greatly since then) is still valued as a clear and readable introduction, especially to certain topics often used in astrophysics. He made incursions into plasma physics as well. But the next topic to which he turned his attention must have surprised everyone. It was the study of self-gravitating rotating masses of a fluid of uniform density. For one thing, the subject was very old, originating in Newton's 'magisterial' (Chandrasekhar's phase) derivation of the figure of the earth. It had already attracted the attention of mathematicians like Jacobi, Riemann, Dedekind and Poincare, to name but a few. Chandrasekhar could see that all was not well here, and in extensive work with Lebowitz, unified and cleared up many aspects, simplifying the mathematics and deriving new results on the way. The achievement was distilled as usual into a book, *Ellipsoidal Figures of Equilibrium*. This severely classical area acquired unexpected relevance with the discovery in 1967 of radio pulsars, which were soon confirmed to be rapidly rotating neutron stars. Since dissipation has a subtle effect on the instabilities of these objects, he was led to include in his studies a form of dissipation caused entirely by an effect of general relativity – the emission of gravitational waves. The electrodynamic analogue is the extra resistance encountered when a charge is accelerated, originating in the loss of energy by radiation. This effect was known from the time of Lorentz, but the gravitational analogue, in spite of work by many people – Einstein, Eddington, Landau and Lifshitz – was riddled with conceptual and mathematical difficulties. A series of papers by Chandrasekhar and his students showed the way by developing the so-called 'Post-Newtonian theory' and deriving, systematically, the gravitational analogue of the Lorentz formula for radiation reaction. In the same period, he also discovered an instability of stars against radial pulsation, again a problem where general relativity made a qualitative change. A well-known astrophysicist has remarked that the work of this period could well have become the content of another classic book. But such a book was never written because by this time the author had now come fully under the spell of Einstein's theory of gravitation, and in particular the black holes, which are an inescapable consequence of that theory (and also his own work on the limiting mass). Unlike on earlier occasions, he was a comparatively late entrant into the area. A whole band of 'relativistic astrophysicists', most of them half his age, were already using pencil, paper, and computer to perturb black holes, scatter all kinds of waves off them, immerse them in external fields, and investigate their properties and stability. The year 1974 brought a heart attack and ultimately major surgery was recommended. He consciously put this off till the fall of 1977 so that he could finish a set of papers on the Kerr solution describing rotating black holes. One of his students has remarked that every complication envisaged by medical textbooks occurred after the operation! It is a measure of his inner strength that he recovered to commence writing *The Mathematical Theory of Black Holes*. This book appeared in 1983 and has a rather different character from its predecessors. It represents his personal efforts to present results in the area (including, of course, many of his own) in a framework which appealed to his own sense of scientific style. Even after all his efforts to find rational and simple ways of doing things, literally hundreds of pages of calculations had to be deposited into archives for scholars of the future. The stability of the Kerr solution could not be fully pinned down. Many things can and have been said of his writings starting from this period Understandably, he no longer found the time and energy to go through all the voluminous literature, and perhaps even the proofreading was not as meticulous as before. The problems investigated could border on the exotic – e.g. two black holes connected by a cosmic string! He himself cheerfully described this apparent retreat from the astrophysically relevant as 'downhill, all the way down'. But to focus on these aspects alone would be to miss the basic point – he had done more 'relevant' work than all the critics combined, and was now following where his mathematical and aesthetic instincts led him. What was truly remarkable was the spirit in which all this work was done, which can only be described as youthful exuberance. Consider his paper on the complicated wave equations describing the motion of a spinning electron in the gravitational field of a rotating black hole. From the time of Euler, the mark of a mathematical physicist has been the ability to 'separate' such multidimensional problems by reducing them to one-dimensional components. This is because there is no standard route or guarantee of success. Many people in the field would have been happy to separate the Dirac equation in the Kerr spacetime, but Chandrasekhar started and finished the calculation on the same evening! In this phase, he would fly to Houston for a day or stop over at Crete or Rome for a week to discuss his latest ideas with his friends and collaborators. A young postdoctoral fellow arrived unexpectedly in the same week as when his Nobel Prize was announced. Who else could have got down to work nevertheless and had the first manuscript on colliding gravitational waves almost ready in two weeks? His last book, in which he undertook to read Newton's *Principia* from the point of view of a mathematical physicist rather than a Latin scholar, again bears the strong stamp of being guided by personal taste and satisfaction. His lectures on this subject conveyed vividly the sense of wonder and awe that reading Newton in the original gave him.

There is so much that can be said of his scientific achievements (many have been omitted above!) and style that there is a real danger of missing other contributions. During his watchful and uncompromising editorship, lasting nearly two decades, the *Astrophysical Journal* grew from near-provincial to international stature. His teaching and his supervision of research students were legendary. Even though he had collaborated with the likes of von Neumann (on stellar dynamics) and Fermi (on galactic magnetic fields), he always said his deepest satisfaction came from interactions with students and younger colleagues. Many of these matters, including his austere lifestyle and deep literary and musical interests, have been extensively documented by Kameshwar Wali in a biography entitled *Chandra* (the name by which Chandrasekhar was widely known but which this Indian pen finds too familiar to use comfortably).

A topic of special interest would be his relationship with two countries – India, where he was born and spent his formative years, and the USA, where he grew to world stature. It is often felt that here is a clear case of a person not finding proper conditions and recognition in his own country. His anguish when he felt that a good person in India was not given his due, or with the growth of hierarchy and bureaucracy in the Indian scientific establishment, has been well documented, for example in Wali's book. Yet his relationship with India does not end there. He was a founding Fellow of the Indian Academy of Sciences at the age of 24, and had an offer to work at the Indian Institute of Science after his stay in England. A serious effort was made to bring him to India as the Director of the (then) Kodaikanal Observatory, and he seems to have treated it with equal seriousness before declining. He retained his Indian citizenship till 1953. On visits to Bangalore in the seventies and eighties, he not only willingly and enthusiastically delivered lectures but also spent time talking to students and young researchers, offering comments and reactions in his inimitable style. In these encounters, one could detect no trace of the alienation, cynicism or bitterness that some would ascribe to him. Culturally, he had deep affinities with India, as he has recorded in a little known essay 'on being a foreigner'.

Coming to the American side of the coin, the current wave of adulation launched by the Nobel Prize is not typical of the reactions to him in earlier years, when recognition was slow in coming and hard-won. An authoritative collection of classic and influential papers in astrophysics edited in 1979 managed not to include a single one by him. Perhaps this atmosphere which he encountered in his early years might even have spurred him to new heights of labour and achievement. This is not the place to draw any firm conclusion about the complex feelings that he must have had for both nations, but one can certainly discount the more simplistic view of the matter that is usually propagated. In any case, when one looks at the totality of the work, the manner in which it was carried out, and the impact on colleagues, students, and even people who encountered him just a few times, questions of nationality seem to fade into insignificance. What will remain is the memory and the legacy of a man who never stopped learning, thinking and working throughout a long life, and was driven both by his sense of what was right and what was beautiful to heights that very few will ever attain.

R. NITYANANDA

Raman Research Institute,
Bangalore 560 080, India.