Chandra: gentleman, scholar and telescope†

*Roger Blandford**

In the course of a long and distinguished career, Subrahmanyan Chandrasekhar, whose centenary is being celebrated, made major contributions to our current understanding of white dwarfs, stellar structure, stellar dynamics, radiative transfer, plasma physics, fluid dynamics, stellar stability, black holes and aesthetics. These topics are briefly introduced and the astrophysical importance of his research is illustrated through reference to results from the Chandra X-ray Observatory, which is named after him.

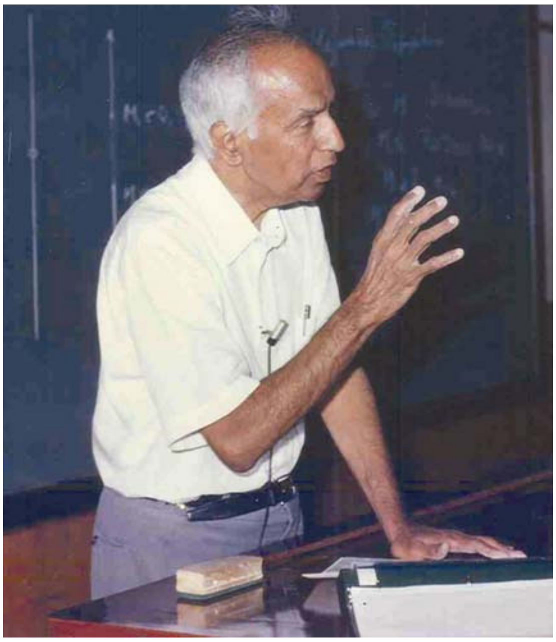
Keywords: Astrophysics, black holes, Chandrasekhar, Chandra X-ray Observatory, white dwarfs.

IN 1974, Subrahmanyan Chandrasekhar, henceforth Chandra delivered the second Ryerson lecture[1] at the University of Chicago, where he was employed. This was not some mathematical discourse on theoretical astrophysics, but a lecture contrasting the patterns of creativity focusing on three of his idols, Shakespeare, Newton and Beethoven, who are joined by stars of greater magnitude (see note 1). Chandra starts by describing himself as a lonely wanderer in the bylanes of physical science, lacking the 'circumference of comprehension' to address himself to his challenge. He requests his audiences' forbearance. Chandra's lecture is of course a jewel of elegantly polished scholarship which has impressed humanities professors as much as those of physics. Let me begin by quoting from the same source that Chandra used to conclude his lecture, Shakespeare's *Henry IV Part 1*.

If you look for a good speech now, you undo me:
for what I have to say is of mine own making;
and what indeed I should say will, I doubt, prove mine own marring.

I know how Chandra must have felt but, in my case the disclaimer is true! I am discussing the impact of one of the lions of astrophysics in the presence of his colleagues, his relatives and his illustrious biographer, Wali (see note 2).

Chandra was born in Lahore[2] in 1910. His uncle was the Nobel laureate physicist C. V. Raman and his cousin, the famous radio astronomer Radhakrishnan (see note 3) Chandra left India for Cambridge in 1930 and then moved to the United States, making his home in Chicago in 1937, where he remained until his death in 1995. Chandra was a singular astrophysicist. His approach was deliberate and highly successful. Somewhat like Newton (see note 4)[3] he would focus on one field where he believed he could make a big difference and systematically solve problems of increasing complexity until he felt that he understood the field very well, had developed a broad perspective and sated his desire for the intellectual beauty that the field yielded up. He would then write a classic text and move on. This took about a decade per field. As a mathematician himself, Chandra had legendary powers of concentration and a formidable mastery of classical applied mathematics (see note 5). Despite his manifest talent, though, Chandra saw beyond the means to the ends and it was general conclusions and major changes in outlook that he was after. Like Beethoven, he wanted to make music for all time, not simply publish scores.



Subrahmanyan Chandrasekhar.

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Roger Blandford is in the Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, CA 94025, USA.
*e-mail: rdb3@stanford.edu

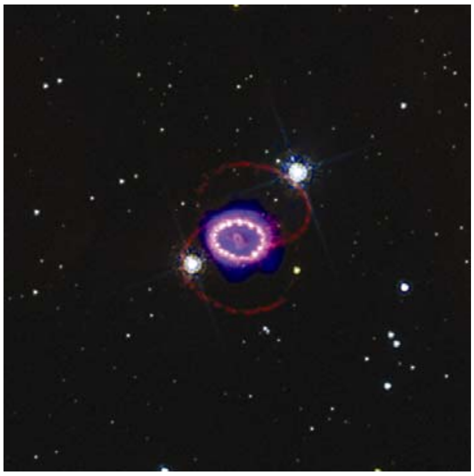
Chandra X-ray Observatory. (Image: NASA/CXO/SAO)

The meeting that we attended is devoted to a celebration of Chandra's life work and it would be presumptuous (and foolish) of me to usurp the contributions of my colleagues. Chandra's *oeuvre* is far too great for that anyway. Instead, I shall use the device of taking results from the X-ray telescope that was named in his honour, the Chandra X-ray Observatory[4] to illustrate the observational impact of his theoretical contributions. Chandra X-ray Observatory, henceforth CXO, was launched on 23 July 1999. I was fortunate to be able to attend the launch which took three attempts. On the second one, I got funnelled into the wrong line and ended up being told to fill a vacant seat next to Chandra's widow, Lalitha, whom I had met briefly on a less frenetic occasion. She was so proud and if force of personality could have got the rocket off the ground, we would not have had to await the third attempt. Anyway, Chandra the telescope – CXO – was launched and has been gloriously successful. It can detect X-rays with energies from 0.1 to 10 keV (see note 6) and, most importantly, has an angular resolution of better than one arcsecond, comparable with that achievable by a large, well-sited, ground-based optical telescope though not, of course, Hubble Space Telescope. This is far superior to that achieved with any previous X-ray telescope, or likely to be achieved by a successor any time soon. The images that it has produced are spectacular.

White dwarfs

Chandra's most celebrated research contribution, for which he was awarded the 1983 Nobel Prize together with Willie Fowler, was to develop a theory of 'white dwarf' stars. These are special stars, of which only three examples were known at the time. They were known to be very compact and they could not be held up by hot gas like the sun. Following work by (a different) Fowler[5] and Stoner[6], and working independently of Landau[7], Chandrasekhar[8,9] assumed (correctly) that white dwarfs are supported by the pressure exerted by 'cold' electrons which respect Heisenberg's famous uncertainty principle. He showed that the average density would increase with the mass of the star until the electrons moved with speeds close to that of light. Soon after this point is reached, electrons are inadequate to oppose the pull of gravity, and collapse of a star more massive than roughly one and a half times that of the sun would ensue. This is not the end of the story. If we were to perform the thought experiment of slowly adding mass to a white dwarf (not what happens in most cases), then the collapse would occur and an even more compact 'neutron star' would be formed. The same argument applies here too, except that it is neutrons not electrons that are supplying most of the pressure and the maximum mass of a neutron star turns out to be closer to twice the solar mass. So according to the principles expounded by Chandra, collapse is unavoidable for a sufficiently massive star. This turned out to be controversial because the 'black hole' (see note 7) that results, asks serious questions of fundamental physics. This led to a legendary dispute with his mentor, Eddington, who publicly questioned Chandra's results, perhaps on the grounds that they were not in accord with Eddington's ephemeral 'fundamental theory' (see note 8). Some of these questions remain, but the reality of white dwarfs, neutron stars and black holes is not now seriously doubted.

CXO regularly observes all three types of compact stars, especially when found with binary companions that donate gas to them, which gets hot as it accretes and radiates X-ray photons. It can also observe gravitational collapse in the form of supernova explosions. Two important examples are a nearby supernova observed in 1987 in the



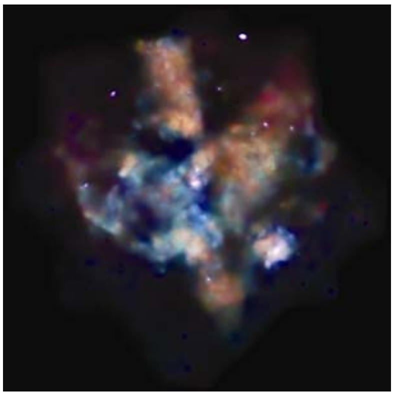
Supernova 1987A. As observed in 2007 on the 20th anniversary of the first observation of Supernova 1987A. (Image: NASA/CXO/SAO)

Large Magellanic Cloud and another one that was observed in the 'grand design' spiral galaxy, M100, in 1979, which is strongly argued on the basis of the strength of its X-ray flux to have left behind a black hole. A related type of explosion that may also lead to the formation of black holes is the gamma ray burst (see note 9). CXO has made many important observations of the 'afterglows' that follow these explosions.

Stellar structure

These path-breaking investigations into white dwarfs stimulated a much lengthier study of stars in general, which led eventually to the publication of his monograph on stellar structure, the first of his major textbooks combining a masterly summary of the field with a wealth of new insights. He paid particular attention to the source of the power – nuclear reactions – and it was this that set his book apart from his mentor and critic Eddington's earlier book on the same subject. He concentrated on describing stars over most of their lives – what astronomers call living on the main sequence – instead of the much less well-defined problems of infancy and senescence, though he did give an extensive discussion of white dwarfs, as might be expected.

CXO has contributed mightily to our understanding of normal stars. We have known for over 60 years that the sun is an X-ray source because it is surrounded in a hot, active corona. Other stars are relatively more luminous in X-rays, and low mass and young stars are especially X-ray active. This has clear and obvious implications for the habitability of extra-solar planets. In fact our closest stellar neighbour, Proxima Centauri, some four light years away, has been seen as a flaring X-ray source. It is a small red star, about an eighth of a solar mass and half the solar temperature. We know that it has no heavy planets, but if it turns out to have Earth-sized companions, then it will be a very interesting exercise to determine whether or not they could be expected to be habitable.

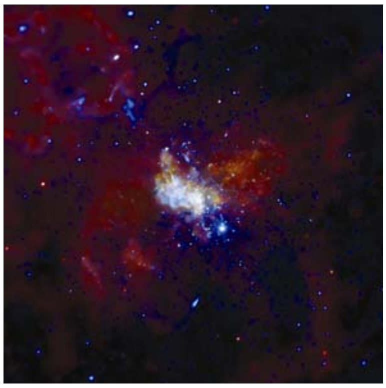


Tarantula Nebula. 30 Doradus is one of the largest massive star forming regions close to the Milky Way. (Image: NASA/CXO/SAO)

Another spectacular result in stellar astronomy is the observation of the star cluster known as the Tarantula Nebula, or 30 Doradus, also in the Large Magellanic Cloud. It is the most luminous nearby example of stars in the process of formation. About half a million solar masses of gas is being transformed into stars mostly within a region less than a 100 light years across. These young stars are highly luminous in their own right. However, they also create supernova explosions which leave behind compact objects and rapidly expanding debris that are also powerful X-ray sources. The optical luminosity of the entire nebula exceeds a million times that of the sun, whereas the X-ray luminosity is a thousandth of this. These observations illustrate how X-ray studies complement optical studies.

Stellar dynamics

Chandra's next big study was into the motion of stars[10]. Although a star, like the sun, may seem very big to us, it is very small on the scale of an entire galaxy of maybe 10 billion stars. In fact, it can be treated as a point, albeit a very heavy point. Now, the motion of this point star is governed by the laws of motion first proposed by Chandra's idol, Newton. Surely, this can be handled by well-understood physics and simple mathematics. At some level that is true, and many modern studies comprise following billions of stars on a computer. However, Chandra did not have access to these facilities and, as a consequence, he found some very important physical effects that might otherwise have gone unrecognized. One of these is called dynamical friction. If one considers an individual star moving in a galaxy, it will orbit the centre of the galaxy in an analogous fashion to the Earth orbiting the sun. However, it will also interact with individual stars and, every time one of these has a close encounter, the star whose motion we are tracking will be slightly deflected. These gravitational nudges are essentially random and so the underlying orbit changes in a correspondingly random way. This



Sagittarius A*. The supermassive black hole at the center of the Milky Way galaxy. (Image: NASA/CXO/SAO) sort of behaviour is sometimes called 'stochastic' and stochastic processes are very common in physics (see note 10).

Now, when Chandra and others studied this in more detail, he found that on average, the collisions would lead to a net loss of energy as, for example, happens with an artificial satellite moving through the upper atmosphere of the Earth. This is called 'dynamical friction'. The timescale for this to affect the sun is many million times its age and indeed the age of the universe. However, a much heavier object, like a star cluster or a small satellite galaxy can sink to the centre of the galaxy in, say, a billion years. This may be one of the most efficient ways to keep the hungry black holes, that lurk in the centres of active galaxies, fed (see note 11).

One of the problems that limits studies of the four million solar mass black hole at the centre of our galaxy is that there is a lot of dust – tiny solid particles – along the line of sight to it. As a result, we cannot see central star clusters using optical telescopes. However, this dust does not obscure our view at X-ray and infrared wavelengths and CXO, working in combination with the Spitzer Space Telescope has uncovered several such examples. Another example of dynamical friction at work involves the massive black holes in the nuclei of captured galaxies. By the time these captured galaxies have sunk to centres of the capturing galaxies, they will have been stripped of most of their stars, leaving behind the black holes and disks of gas that orbit them. Disks orbiting black holes can create jets that are launched in either direction, perpendicular to the surface of the disk and which can then emit X-rays. What CXO occasionally sees are two jets with large, symmetric kinks that are produced by one black hole orbiting another. These black-hole orbits are likely to shrink over time and eventually the black holes will merge emitting a giant burst of gravitational radiation.

Radiative transfer

The next big project was to systematize the study of radiative transfer[11]. The major application of radiative transfer for astronomers was to the outer atmospheres of stars. As they make their final dash for freedom, the photons that we see with our eyes and telescopes are absorbed and re-emitted as well as scattered by molecules, atoms, ions and electrons, and the rate at which this happens depends upon the energy of the photon. If the photon resonates with an individual type of atom, say, then it will travel a shorter distance between interactions and be observed from high up in the atmosphere where the temperature is lower than the site of the final interaction of a non-resonant interaction. As a consequence, the observed spectrum exhibits dark 'Fraunhofer' lines at the frequencies corresponding to these resonances. Historically, this was the source of much understanding about the atoms in the periodic table of elements, most famously helium. By the time Chandra became interested, physicists (see note 12) working on developing quantum mechanics, had a nascent theory of atomic processes and most of the observed absorption lines could be identified. However, it was also necessary to following the drunken journeys of individual photons as they careen from one interaction to the next. The mathematical formalism that is used to handle these problems is known as the theory of radiative transfer and this is where Chandra made his big contributions. He was particularly concerned with the polarization of the emerging radiation as he knew that this would be a powerful diagnostic of the physical conditions in the underlying atmosphere. His work also plays off an important dualism in the treatment of radiation. One can either regard radiation as a collection of discrete photons, or one can treat it as a continuously changing intensity. The trick is to use the approach that gives the most accurate results, and Chandra was a master at this due to his deep understanding of statistical methods.

The theory of radiative transfer has found much broader application than astrophysics. It is crucial to our understanding of nuclear reactors, laser physics and, most relevantly today, the Earth's atmosphere and the causes and implications of the accumulation of carbon dioxide. Even within astrophysics, it is central to our attempts to understand how supernova explosions happen, as the escape of neutrinos which have a large role is a radiative transfer problem. Naturally, 21st century radiative transfer is largely computational, but it still rests upon the principles that Chandra was so careful to explain. This raises an interesting question in my own mind. Suppose Chandra had been born 50 years later with his mathematical gifts intact, would he have still written lengthy equations with pen and paper? (see note 13) Or, would he have embraced numerical methods, recognizing their immense power and out-programmed the rest of us? I suspect the latter.

Turning now to CXO, there is a very nice example of radiative transfer that connects us to a later theme. We now know that black holes are abundant in the universe. Their masses range from a few to billion times solar. We do not observe the black holes directly; instead we see X-ray emission from gas that swirls around the black hole in an accretion disk. This gas slowly spirals inward and, before being swallowed by the hole, it is heated by friction to temperatures similar to that found in the centre of stars. Now an accretion disk has an atmosphere, just like the sun. It can form absorption lines and emission lines, which are bright not dark, just like some other stars. There is, however, a crucial difference. The disk orbits with speeds that approach that of light close to the hole's event horizon. When a photon is emitted by moving gas, its energy will be Doppler-shifted to greater and lesser values. The net effect is that the line will be much broader (in energy) than a line from the sun. The so-called gravitational redshift – the loss of energy by a photon as it climbs up the strong gravitational field – also contributes to the shape of line. Lines are formed by different elements, most notably iron, and they involve a process called fluorescence, which involves the excitation of an ion by an even more energetic photon than the one that is emitted. How all this happens is still a matter of some debate, but the lines are clearly seen in both active galactic nuclei and black-hole binary stars. It turns out that the widths in energy of the lines are sensitive to the rate of spin of the black hole. If the spin is high and the gas orbits in the same sense, then the accretion disk will extend in close to the event horizon, and the line will be very broad. This is one of the best techniques we have to measure the spin rates of black holes, and it turns out that most of the ones we see are spinning rapidly.

Another stunning example of radiative transfer at work involves a pulsar known as B1509-58 that spins on its axis seven times per second. The spinning neutron star loses energy at a very fast rate in the form of electromagnetic field and particles, and this is converted into X-ray photons which illuminate the surrounding gas. What we see depends upon radiative transfer.

Plasma physics

The structure of stars and the transfer of radiation are intrinsically quantum-mechanical issues. The motion of stars in the galaxy is not, and relies upon 'classical' physics. Chandra's next topic[12] – plasma physics – involves the motion of electrons and ions in electromagnetic field which behaves in accord with Maxwell's famous equations, and quantum-mechanical effects are also relatively unimportant. Plasmas have a strong propensity to exhibit 'collective' effects. The individual particles do not move independently. Instead they move together in a large variety of 'modes' creating the currents and charges which sustain the electromagnetic field. Again the duality between the motions of individual particles and the behaviour 'in concert' is a strong feature of his textbook. Although most early studies of plasma physics were responsive to discoveries about the ionosphere, and interplanetary and interstellar media, the contemporary driver is undoubtedly the programme to bring about controlled thermonuclear fusion in magnetically confined rings of hot plasma, sometimes called tokamaks. Although the scale is much smaller than that encountered in astrophysics, many of the most important physical processes are manifest in both environments.

One process that is not a feature of typical laboratory plasmas is the strong shock front. Shock fronts exist in fluids, like air, when a gas flow decelerates from a speed faster than sound to slower than sound. This happens with the flow around the space shuttle Columbia that launched CXO, for example. As was recognized in the nineteenth century, the deceleration can happen quite abruptly in a shock front. If we move with the shock, the air flows into the surface from one side at high speed, faster than the speed of sound, and leaves from the other side at low speed, slower than the speed of sound. The air is heated by passage through the shock front and if the heating is great, the shock is said to be strong. Now, air comprises individual molecules which collide every time they move about a tenth of a micron, and this is the typical thickness of a shock front in air. A molecule entering the shock front will quickly encounter a population of other molecules moving at vastly different speeds and will quickly share its energy with them. The situation is rather different with a high-temperature plasma. Instead of molecules, we have ions – in the case of hydrogen, individual charged protons. These can also collide, but the distances that they have to travel in order to do so are very much larger than with air molecules and it might be thought that shocks do not form in plasmas. However they do, and they are routinely observed around the Earth, which moves supersonically relative to the solar wind plasma flowing away from the sun. These 'collisionless' shocks are mediated by collective interactions involving large changes in electric and magnetic fields. We can observe them, for example, surrounding supernova explosions and this is where most cosmic-ray particles, the high energy protons, electrons, etc. which continuously hit the Earth's magnetosphere, are thought to be accelerated. Cosmic rays have long been an Indian research speciality and we know now that they are accelerated up to energies nearly a trillion (see note 14) times their '$E = mc^2$' rest mass energies (see note 15).

At the time Chandra wrote his book, shocks were mostly a theoretical construct and their properties largely conjectural. However, this did not inhibit him from solving a (relatively!) simple problem, namely what would happen to a charged proton spiralling around a uniform magnetic field if it encountered a strong shock wave moving perpendicular to the direction of the magnetic field. He presciently demonstrated that the particle would gain energy, complementing a very famous suggestion by

PSR B1509-58. A 1700-year-old pulsar and its nebula, located about 17,000 light years from Earth. (Image: NASA/CXO/SAO) his illustrious Chicago colleague, Enrico Fermi, made roughly a decade earlier[13]. In fact, the more relevant circumstance turns out to be what happens when the shock wave propagates parallel to the magnetic field and elaborations of this problem underlie the contemporary discussion of cosmic-ray acceleration. Here it is envisaged that cosmic rays, which have speeds much greater than the shock wave, cross the shock front many times on average, being scattered by magnetic disturbances on either side. Every time they cross the shock, they get a small kick in energy and these add up to a major change. This can happen at any energy provided the shock front is large enough.

CXO has greatly advanced our understanding of how cosmic rays are accelerated. It has made detailed images of prominent supernova remnants in our galaxy and allowed us to reconstruct details of the explosion, but determining the location, state and velocity of the different elements synthesized. It has revealed how gas flows after it has shocked and confirmed that relativistic electrons and protons are made at shock fronts. Thirdly, working in conjunction with a gamma-ray satellite named after Fermi, CXO has shown that cosmic rays are accelerated to even larger energies than expected and that shock waves not only accelerate cosmic rays, they also amplify magnetic field (see note 16).

CXO may also be contributing to our understanding of the acceleration of the highest energy cosmic rays, not by shock waves associated with supernova remnants, but perhaps by shocks associated with clusters of galaxies. Rich clusters, like Abell 1689, containing thousands of galaxies, are among the prime targets of CXO. This is because they also contain dense concentrations of hot, X-ray-emitting gas, all held together by the gravitational pull of the underlying dark matter (see note 17). By carefully measuring the temperature and density in the outer parts of clusters, it has been possible to show that the gas is extremely hot relative to its density in comparison with the general intergalactic medium. The only reasonable way to have got into this state is to have passed through a strong shock front formed when relatively cold gas falls highly supersonically onto the cluster. These shocks are essentially invisible, but they show up in numerical simulations of the growth of structure in the expanding universe. They are very large, perhaps ten million light years in size, and provide an ideal site for accelerating the highest energy cosmic rays. This leads to two testable predictions, that the very highest energy particles be iron nuclei, not protons and that high-energy cosmic ray production decreases as the universe expands.

Fluid dynamics

As might be expected, following the individual particles around, as one does in plasma physics, is a far more challenging endeavour than simply treating them in bulk, as one does in fluid dynamics. Fluid dynamical instabilities are everywhere. Convection, the excitation of waves on the ocean and the turbulence that trails a jet aircraft are three familiar examples. A book by Chandrasekhar[14] is a thorough and didactic account of the conditions under which a wide variety of instabilities actually occur. An important extension of fluid dynamics occurs when the fluid is electrically conducting and we can call this magneto-fluid dynamics (MFD) (see note 18). Electrical conductivity allows the fluid to dictate terms to the magnetic field and, conversely, the magnetic field to exert a force on the fluid (see note 19). As already mentioned, magnetic plasma confinement devices designed for promoting nuclear fusion have attracted a lot of attention, and these can be handled using MFD. The simplest such example, which is quite instructive is a pinch. This is an extended column of plasma with a current flowing along it. The current creates magnetic field lines that wrap around the pinch like the iron hoops that hold the staves of a barrel together. This is not a promising fusion device because plasma can escape easily through the ends of the pinch. However, it is a very instructive example. It turns out to be quite unstable. For example, if the radius of the pinch is reduced somewhere along its length, then the radius will continue to get smaller until the pinch is destroyed (see note 20). Tokamaks which are like pinches with the two ends joined, have to be carefully designed to avoid many instabilities like this to which they are prone.

Even if there is not a strong external magnetic field in the picture, the fluid will commonly generate one as happens, for example, in the outer core of the Earth or the interior of the sun. This is known as a dynamo, which can also be thought of as a consequence of an instability in a fluid flow. Chandra, and independently Velikhov[15], discovered an important instability that would lead to the rapid growth of a small field in a conducting accretion disk orbiting a black hole or neutron star. This effect,

Abell 1689. A massive cluster of galaxies located about 2.3 billion light years away. (Image: NASA/CXO/SAO) which was re-discovered in more recent times, is now called the 'magnetorotational instability'. It is believed to ensure that accretion disks that are hot enough to convert the orbiting gas into plasma, which is highly conducting, will all contain large magnetic fields.

Not surprisingly, CXO has seen many examples of fluid dynamics in action. Among the more dramatic are those associated with accretion disks orbiting black holes and neutron stars. As mentioned above, if these disks comprise plasma, they will be highly conducting and the fact that their orbital periods vary with radius – just like the planets – means that the magnetorotational instability will operate and magnetic field lines will be carried around by the orbiting gas. As also mentioned, many accretion disks also exhibit jets, twin outflows of magnetized plasma that were first observed by optical and radio astronomers, but are now commonly seen by CXO with its fine angular resolution. These jets are launched perpendicular to the accretion disks and can reach speeds close to that of light. They have to be confined and magnetic field lines wrapped around them is strongly implicated. Now, if we think about what we learned about pinches, then we might expect these jets to be violently unstable. However, quite the converse is seen, for example, in the source Pictor A, which is astonishingly straight. We suspect that it is the rapid motion of the outflow that is responsible for the apparent stability. Simulations do appear to bear this out, but still we have to be impressed!

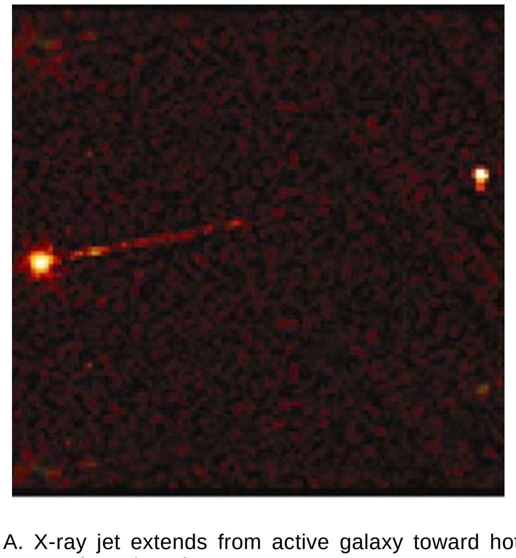
A very good example is provided by M87, the central galaxy in the Virgo cluster of galaxies. It has a central black hole whose mass has just been re-measured to over six billion suns. The jets can be traced down to distances of order a hundred times the size of the black hole. These jets are observed from the lowest radio frequencies to the highest energy gamma rays and the X-ray emission is created by electrons of very high energy, as large as the highest energy cosmic rays made by supernova explosions. So, jets have to be very efficient accelerators of these electrons which lose their energy very rapidly. We are not at all sure how this happens, but shocks are unlikely to be responsible. We must instead invoke new mechanisms and this is one of the great puzzles.

Another discovery is that jets are created by single neutron stars without accretion disks. Again it is the twisting of magnetic field lines attached to the spinning star that is likely to be at work, but the details are highly controversial. As these jets are contained within supernova remnants that expand relatively slowly, it should not surprise to discover that the outer parts of the jets are seen by CXO to thrash around. In other words, they are unstable.

Ellipsoidal figures of equilibrium

One of the most fascinating developments of Newton's laws is the study of spinning liquids. The simplest example involves computing the oblateness of a uniformly-spinning and constant density earth. This problem was solved by Newton. A more general problem, as defined and explored by MacLaurin, Jacobi, Dedekind and Riemann, is to describe spinning, self-gravitating fluid bodies of constant density. This last restriction is pretty unrealistic when it comes to describing real stars, planets, galaxies, etc. Furthermore, the way the classical problem is set up restricts the types of flow that are included. Nonetheless, the problem, as extensively explored by Chandra is a mathematician's playground and highly instructive for the more practically minded physicist[16]. Unexpected solutions and their stability can be carefully analysed, and the results turn out to be quite generic. Not surprisingly, Chandra's treatment is pretty formal and separate from astrophysical application, but even here, the principles that he formulated and used are applicable to galaxies and clusters of galaxies, and can be used to delineate the distribution of the dominant mass contribution in the universe, dark matter. Furthermore, general relativity figures prominently in his treatment, which provided a bridge to his final research endeavour.

One very important conclusion that has emerged from these applications concerns the nature of dark matter itself. As first demonstrated by a combination of CXO and Hubble data, the 'bullet' cluster of galaxies, which is actually being assembled from the merging of two smaller clusters, shows that the dark matter interacts solely through the force of gravity while the hot gas, which is responsible for the observed X-rays, also interacts through fluid dynamical forces and forms shock fronts. This implies that the dark matter comprises effectively collisionless particles. The hot gas is a plasma and its fluid properties are ultimately due to electromagnetic field. The dark matter shows none of these properties, consistent with its identification with electrically neutral, weakly interacting elementary particles.

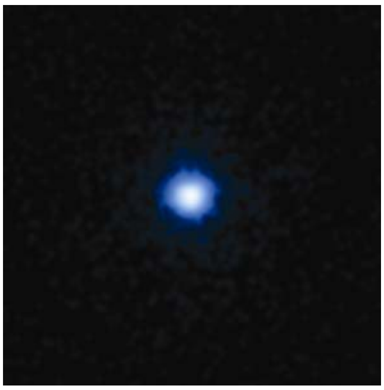


Pictor A. X-ray jet extends from active galaxy toward hot spot. (Image: NASA/CXO/SAO)

Black holes

Chandra's final research effort was concerned with the mathematical theory of black holes[17]. In many ways he was returning home after an extended intellectual odyssey. The problem of gravitational collapse, that his researches on white dwarfs had uncovered and which had so troubled Eddington, now commanded his full attention. He had much to think about. Soon after the publication of the general theory of relativity in 1915, Karl Schwarzschild had found an exact solution of the equations, which we now recognize as describing a non-rotating black hole. This solution failed at a particular radius, now called the Schwarschild radius. We now know that this failure is no more significant than the failure of latitude and longitude to characterize the north or south pole of the Earth (see note 21). There was much confusion about the meaning of this solution. In one interpretation it predicted that an overmassive, compact star would collapse to infinite density, a 'singularity', where the known laws of physics become unusable. Another view was this never happens because the collapse would appear from the outside to stop at the Schwarzschild radius. A third view was that departures from spherical symmetry would save the day and finally, Eddington was sufficiently troubled by this conclusion that he opined that something must intervene (teleologically) to prevent it. We now know that the first view, as essentially spelled out in 1939 by Oppenheimer and Snyder[18], is correct. Black holes can, must and do exist. As with dark energy, we should not allow the affront that they present to the *amour propre* of theoretical physicists to distract us from more important considerations.

Bullet Cluster. A collision of two large clusters of galaxies about 3.8 billion light years away. (Image: NASA/CXO/SAO)



GRB 110328A. A gamma-ray burst located about 3.8 billion light years from Earth. (Image: NASA/CXO/SAO)

In 1963, Roy Kerr[19] discovered a remarkable generalization of Schwarzschild's solution which describes a rotating black hole. Subsequent work demonstrated that astrophysical black holes have a unique geometry characterized by mass, which just sets the scale, and spin which is one number – all that is needed – to fix the shape of the space–time (see note 22). Black holes have extraordinary mathematical and physical properties, and Chandra worked tirelessly on the former to extend our understanding of their properties and to elucidate the seemingly magical properties of Einstein's equations and the reasons for their stability. CXO has been concerned with the latter. It has confirmed that black holes are abundant in the universe. Essentially every normal galaxy contains a massive one in its nucleus and each galaxy is likely to contain approximately a million stellar holes. Intermediate-mass black holes may also exist. We know that when holes are fed with gaseous fuel, they can convert its rest mass energy into photons with very high efficiency, perhaps a hundred times that of nuclear reactions. This also points to the prevalence of high spin among observed black holes, as spin is conducive to high efficiency. In fact, there are two ways this can happen. First, the accreted gas can release its gravitational energy as it approaches the even horizon through friction. Alternatively, it can spin up the black hole, which can subsequently release its energy through some form of 'Penrose'[20] process. The most likely way to effect this release is through the agency of electromagnetic field, rather like what happens with a pulsar. There is a lively debate as to whether the jets derive most of their power from the spinning hole, or from the accretion disk. The answer is highly likely to emerge from a combination of observations, especially using CXO and numerical simulation.

The genesis of black holes is another subject of great interest. Stellar holes may be made in gamma-ray bursts. They are also likely to result from the coalescence of binary neutron stars. Another possibility brought to light by CXO is through the coalescence of binary white dwarfs and one of these has already been found with a 5 min orbital period. In ten thousand years, another black hole will be formed.

Conclusion

I hope that in this brief and inadequate overview of the work of Subrahmanyan Chandrasekhar, I have managed to convey to a general audience the depth, breadth and prescience of his scientific contributions. The observatory which bears his name is equal to these contributions and continues to delight, surprise and stimulate us all. Let us hope that the next large X-ray telescope to be launched, the Indian satellite, ASTROSAT, due for lift-off in 2012, will do likewise.

Notes

1. For an astronomer, a star of greater magnitude is not as luminous. As my audience will be aware, 'chandra' translates in Sanskrit as 'luminous'.
2. As someone who does not believe in the inheritance of acquired characteristics, I cannot hope that my academic lineage as his great, great nephew will do me any good!
3. I write this having just received the sad news of the passing away of 'Rad'. He will be sorely missed in the world of astronomy that he did so much to advance and enliven.
4. Chandra payed extraordinary homage to Newton with his commentary on Newtron's masterpiece, *Philosophiae Naturalis Principia Mathematica*.
5. I recall, as a graduate student, hearing Chandra deliver a lecture on rotating figures of equilibrium and showing one equation that occupied three hand-written transparencies – John Archibald Wheeler speaking at the same meeting insisted on using coloured chalk! Someone in the audience questioned if there was a sign error on the second transparency. I thought this was a joke, bordering on *lèse majesté*, but Chandra took the question seriously, thought for a while, and then agreed with the questioner!
6. A unit of energy for the X-ray photons.
7. This coinage was not made until 1968 by Wheeler.
8. Despite the dispute, there is abundant evidence that Chandra and Eddington had the highest regard for each other's accomplishments[1,2].
9. One example is dubbed the 'Beethoven burst' because it was observed on Beethoven's birthday. I hope Chandra would have approved.
10. As I came here today through the Bangalore traffic, the driver had a pre-determined route from which he continuously departed due to interactions with other cars. Also, as with stars there were no direct collisions, though plenty of near misses!
11. On a personal note, my first encounter with Chandra involved dynamical friction. As a graduate student, I had read his book and wanted to apply the theory to a quite different problem. However, I was having problems following the treatment and I wrote to Chandra suggesting what seemed like a better way to arrive at his results. I do not have my letter which I suspect may have been less than deferential. However, Chandra's response was rapid, gracious and detailed, and he pointed me to more references where I found what I needed.
12. Including Chandra who calculated the absorption coefficient of negative hydrogen which is very important in the solar atmosphere.
13. Chandra was famous for orienting the paper in what his much younger colleagues would recognize as 'landscape' mode.
14. One trillion is ten kharab!
15. The fastest cosmic rays have energies similar to those that Sachin Tendulkar must impart to a cricket ball in order to score a six!
16. This is apposite because the two papers on which Chandra and Fermi – two very different types of scientist – collaborated were about magnetic fields in the interstellar medium.
17. Studies of X-ray clusters provided the first measurements of the incidence of dark matter on the scale of the universe and are now being used to measure the properties of dark energy.
18. I prefer this name to the one Chandra actually used because water – a poor electrical conductor – is rarely the subject of its attention.
19. To be more precise, if the conductivity is high, the magnetic field is dragged along by the fluid and what is special about the magnetic force is that it is directional, positive in some directions, negative in others. In the language of pop psychology, these two features can be styled 'go with the flow' and 'push–pull'.
20. This is sometimes called the 'sausage' mode, which helps illustrate what is happening.
21. Eddington, himself contributed to this understanding, but does not appear to have appreciated what he had discovered.
22. A further generalization includes electrical charge, but this is unimportant astrophysically.

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