Chandra's X-ray Vision

K P Singh

Kulinder Pal Singh is in the Department of Astronomy and Astrophysics of the Tata Institute of Fundamental Research, Mumbai. His main research area is X-ray astronomy in which he is working since 1973. His primary fields of research are studies of very hot coronal plasmas in stars, galaxies and clusters of galaxies, and studies of nuclear regions of galaxies and accreting supermassive black-holes. He is also interested in the development of X-ray imaging telescopes based on focusing technqiues.

Chandra X-ray Observatory (CXO) is a scientific satellite (moon/chandra), named after the Indian-born Nobel laureate Subrahmanyan Chandrasekhar – one of the foremost astrophysicists of the twentieth century and popularly known as Chandra. The satellite was launched from Columbia space shuttle by NASA on July 23, 1999 and placed in a highly elliptical orbit around the Earth. With a perigee of 10,000 km and an apogee of 140,000 km, CXO reaches one-third of the distance to the moon. CXO is 13.8 metres long and its solar arrays have a wingspan of 19.5 metres as shown in *Figure* 1. The in-orbit mass is about 4500 Kg. Carrying a large X-ray telescope capable of producing the sharpest X-ray images of stars and galaxies, it is designed to study X-ray emission from all types of astronomical objects – faint normal stars in our galaxy to bright and distant quasars. Observations with Chandra will advance our understanding of white dwarfs, neutron stars and black-holes – the end products of stellar evolution, just as the late S Chandrasekhar did in his real life. After a brief period of testing of its instruments, Chandra opened its X-ray eyes on 13th August 1999, and on 26th August 1999, started to send us spectacular images of X-ray emitting objects in the Universe. Unprecedented in its capability to produce sharp X-ray images, a feature unlikely to be surpassed in the near future, these images and their spectral content have already led to a string of spectacular discoveries.

X-ray Astronomy

X-rays from cosmic objects provide information about matter in very high gravitational fields such as are found around the collapsed stars (e.g., black-holes, neutron stars and white dwarfs) that suck matter from around them or their companions. X-rays also tell us about the highest temperature objects and plasmas in

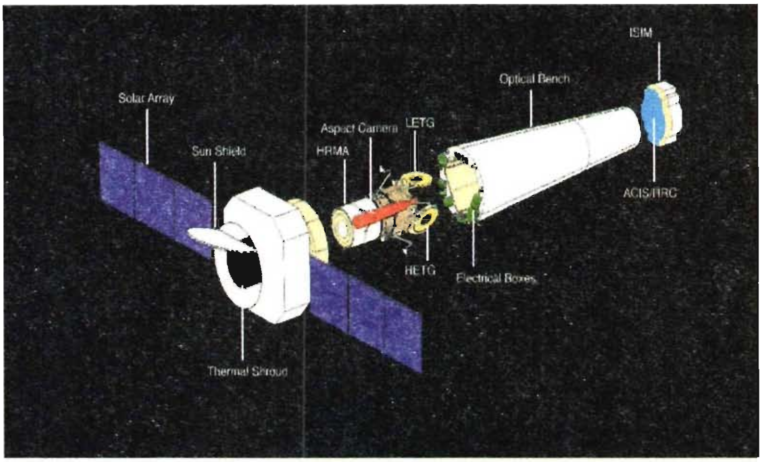


Figure 1.

the Universe (for example, coronae of stars, matter ejected from stars in winds and explosions of stars, matter trapped and heated in the deep gravitational potential of galaxies and clusters of galaxies, etc.). X-rays also probe the conditions around extremely high magnetic fields (e.g., around neutron stars).

X-rays are absorbed by the atoms in the earth's atmosphere. Therefore, to detect them, X-ray telescopes have to be made such that they can be launched in rockets, satellites or high altitude balloons and sent above the absorbing layers of our atmosphere. The history of X-ray astronomy is thus intimately tied up with the progress in space technology. Some of the most famous satellites that have provided a wealth of data in X-ray astronomy prior to CXO are: Uhuru (Freedom in Swahili) launched by USA from Kenya in 1971, High Energy Astronomical Observatory (HEAO) – 1 (USA, 1977), Einstein Observatory (USA, 1978), EXOSAT (Europe, 1983), ROSAT (Germany-UK-USA, 1990), Advanced Satellite for Cosmology and Astrophysics (ASCA – Japan-USA, 1993), and Beppo SAX (Italian-Dutch, 1997). The launch of CXO is a major advance in the history of X-ray astronomy brought about by improvements in the state of the art of instrumentation.

Chandra's X-ray Telescope

The X-ray telescope is the heart of the Chandra observatory.

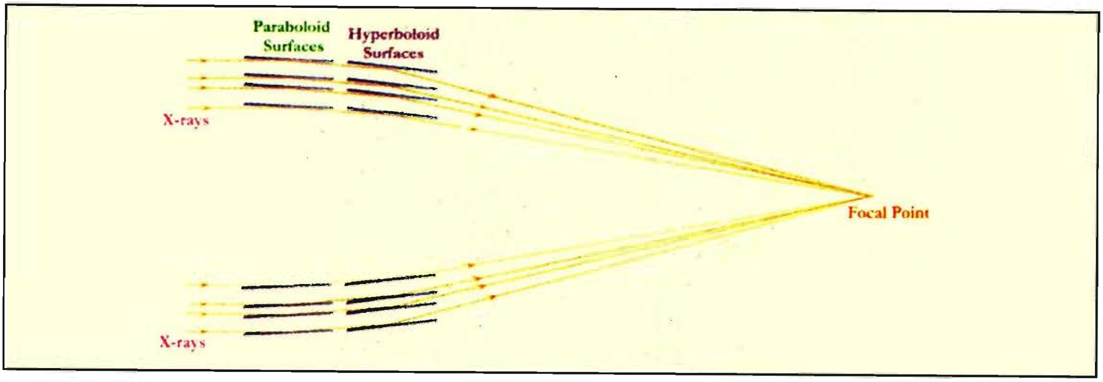


Figure 2a. A schematic of the grazing incidence of X-ray telescope, showing how the X-rays ricochet off the mirrors.

Because of their high energy, typically 100 eV to 10,000 eV, X-rays usually do not reflect off mirrors the same way that visible light does. Instead, they penetrate the mirrors like bullets slamming into a wall, except when they hit at a grazing angle that is less than the critical angle of reflection (about 1 degree) which is proportional to the square-root of the density of the surface material and inversely proportional to the energy of the photon. Therefore, X-ray telescopes have to be suitably shaped and aligned nearly parallel to incoming X-rays. In addition, the surface of an X-ray telescope must be coated densely and smoothly with a metal with high atomic number e.g., gold, platinum, iridium, etc. Smoothness is required to reduce the scattering of X-rays.

A commonly adopted shape and geometry consists of an outer paraboloid surface followed by a hyperboloid surface with a common focus as shown in *Figure* 2. Four nested mirrors, as used in CXO, are shown here as they increase the total reflecting area which is very important to increase the sensitivity of the telescope. This kind of optics is known as Wolter-I optics, named after a German scientist. The first such imaging X-ray telescope (a single set of mirrors) was made by a team of scientists at American Science and Engineering in Cambridge, Massachusetts, USA and flown on a small sounding rocket in 1965. It had taken pictures of the million degree hot solar corona (upper atmosphere of the sun). This was equivalent to the telescope used by Galileo in visible astronomy. Chandra's X-ray

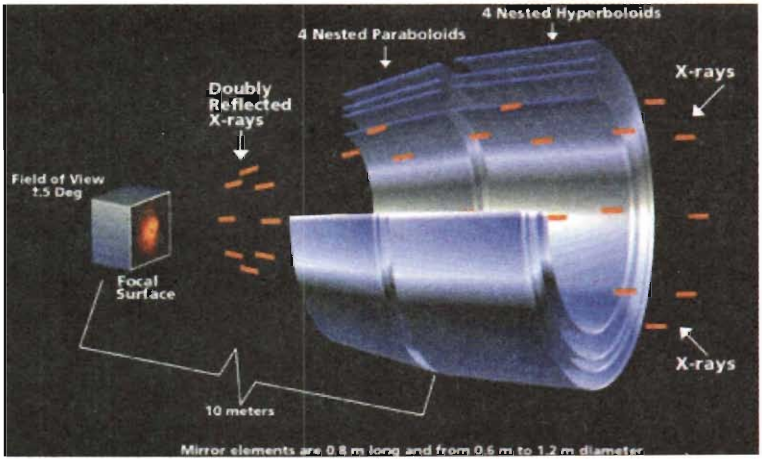


Figure 2b. X-ray astronomy: Chandra.

telescope is based on the principle of *Figure* 2. It has mirror elements that are 0.8 metres long and have diameters ranging from 0.6 metre to 1.2 metre. Its mirrors are polished to a smoothness of a few atoms. The task of shaping to exact figures of paraboloids and hyperboloids, and polishing was done by Raytheon Optical Systems in Danbury, Connecticut and Optical Coating Laboratories, Inc., in Santa Rosa, California. The mirrors were then coated with the highly reflective rare metal, iridium. The coated mirrors were assembled into a support structure called the high resolution mirror assembly and aligned precisely by the Eastman Kodak Company in Rochester, New York. The alignment of the mirrors from one end of the mirror assembly to the other (2.7 meters) is accurate to 1.3 microns or about one fiftieth the width of a human hair!

CXO's telescope produces X-ray images that are 25 times sharper than previous X-ray telescopes, and has 100 million times better sensitivity than the first X-ray telescope.

The telescope system and the scientific instruments were put through thousands of individual tests in an X-ray calibration facility especially constructed for this purpose by the Chandra support team at Marshall Space Flight Center, Alabama. The telescope system, instruments, and spacecraft were put together and tested for space-worthiness at TRW in Redondo Beach, California. CXO's telescope produces X-ray images that are 25 times sharper than previous X-ray telescopes, and has 100 million times better sensitivity than the first X-ray telescope. CXO is thus equivalent to the Hubble Space Telescope in visible

With the launch of CXO, X-ray astronomy has taken just 34 years to reach the same sensitivity that took visible astronomy 380 years!

astronomy. With the launch of CXO, X-ray astronomy has taken just 34 years to reach the same sensitivity that took visible astronomy 380 years!

X-ray Instruments on board Chandra

The mirrors of the telescope focus X-ray photons onto detectors placed at a distance of about 10 meters from the telescope surface (*Figure* 2). The detectors record the number of photons and their direction, arrival time and energy. Two different sets of detectors that have been provided for the above tasks are: ACIS (Advanced CCD Imaging Spectrometer) and HRC (High Resolution Camera). At a time only one of these instruments can be placed at the focus using a sliding mechanism. In addition, two circular structures carrying objective transmission gratings viz., LETG (Low Energy Transmission Grating Spectrometer) and HETG (High Energy Transmission Grating Spectrometer), can be inserted into the path of the X-ray beam just where it emerges from the X-ray telescope. The X-rays dispersed by these gratings are detected by ACIS or HRC. The gratings provide high spectral resolution.

ACIS and HRC are cameras that are well matched to capture the sharp images formed by the mirrors. The HRC Imager consists of a Micro-Channel Plate of 100 mm square size and covers a field of ~0.5 degree (size of the moon) in the sky. It can measure the position of a photon induced charge cloud to an accuracy of 18 microns or 0.37 arc secs, and its arrival time to an accuracy of 16 micro seconds. The ACIS Imager is a 2×2 array of charged coupled devices (CCDs) – sophisticated versions of the crude CCDs used in digital cameras (camcorders), and covers a field of 16×16 arcmin^2. Each CCD has 1024×1024 pixels of 24 microns (0.5 arcsec) size. ACIS also provides X-ray energy information with a resolution of about 100 eV in the energy range of 0.4 to 10 keV.

Detailed information about the X-ray energy (one part in thousand) is provided by the LETG and HETG spectrometers consisting of an array of gold transmission gratings which can be brought into position behind the mirrors. Gratings intercept the X-rays reflected from the mirrors and diffract them, changing their direction by amounts that depend on the X-ray energy, much like a prism separates light into its component colors. One of the focal plane cameras, either HRC or ACIS, detects the location of the diffracted X-ray, enabling a precise determination of its energy. A different set of micro-channel plates (HRC-S) – 300 mm × 30 mm, with 3 sections following the Rowland circle geometry are used here. Alternately a 1 × 6 array of CCDs (ACIS-S), again tilted likewise, can be used. LETG gratings can cover an energy range of 0.1 to 2 keV, whereas HETG gratings cover an energy range of 0.4 to 10 keV.

The science instruments are controlled by commands transmitted from the Operations Control Center in Cambridge, Massachusetts. Data collected by observations with Chandra are stored on a recorder and later transmitted every eight hours to the Jet Propulsion Laboratory, Pasadena, and then to Operations Control in Cambridge, Massachusetts for processing and analysis by scientists. All the sub-systems of CXO are shown in *Figure* 1.

Chandra has already sent us some of the best X-ray images leading to many scientific discoveries in all kinds of objects – of stars, supernovae and supernova remnants in the Milky Way, of galaxies and clusters of galaxies far away, and of quasars in the very remote reaches of the universe.

Chandra's Discoveries

Chandra has already sent us some of the best X-ray images leading to many scientific discoveries in all kinds of objects – of stars, supernovae and supernova remnants in the Milky Way, of galaxies and clusters of galaxies far away, and of quasars in the very remote reaches of the universe. Some of these pictures are presented below with brief explanations to illustrate the discovery potential of CXO.

Supernova Remnants and Supernovae

The official 'first-light' image from Chandra, shown in *Figure* 3, is of a 320 year old supernova remnant, Cas-A in the constellation of Cassiopeia. This picture, taken with ACIS, is remarkable for two important discoveries – detection of a point source at the

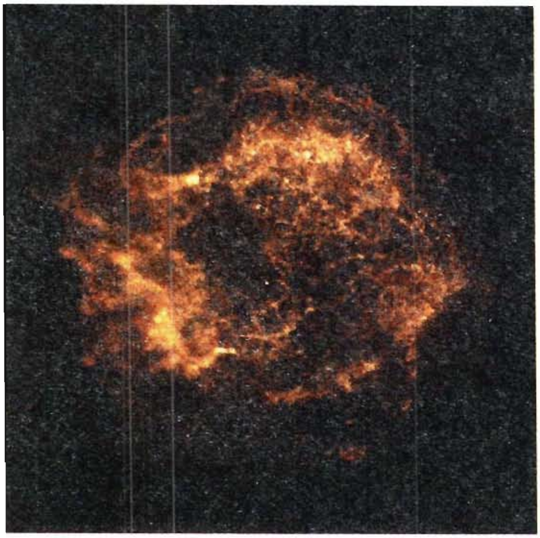


Figure 3.

geometrical centre of the exploded star, and the distribution of spectral features across it. Finding the nature of the central object i.e., whether it is a neutron star or a black-hole, is very important to understand the physics of stellar explosions which occur when the fuel that keeps the stars shining is exhausted. The present data are unable to distinguish unambiguously between the two possibilities. The spectrum of the point source when fitted with a black-body gives a temperature that is too high compared to the theoretically expected temperature from a 320 years old neutron star and its radius is much smaller than the 10 km radius of a neutron star. The point source emission, therefore, could be either from hot-spots on neutron star surface or a black-hole accreting from an accretion disk created by the ejected matter falling back on the black-hole. Longer observations with Chandra in future are expected to clear this mystery.

Analysis of X-ray spectral information obtained from the extended X-ray emission tells us about the nucleosynthesis processes. All the heavy elements known to us, for example, oxygen, silicon, sulphur and iron, etc., are cooked in such processes. Spectral analysis performed on data in *Figure* 3 has shown that X-ray emission arises from a thermally heated plasma and contains : (a) iron-rich ejecta produced by explosive silicon burning, (b) silicon-rich ejecta produced by explosive oxygen burning, (c) the iron-rich ejecta surprisingly lying outside the Si-rich ejecta, indicating a spatial inversion of a significant portion of the supernova core during the explosion, and (d) well-defined filaments produced by synchrotron emission from high energy electrons accelerated in the supernova shock. Another sensational picture taken by Chandra is that of the Crab Nebula shown in *Figure* 4. The remnant of an explosion of a star observed in 1054 AD, Crab Nebula is located 6000 light years away in the constellation of Taurus, and is a strong source from radio through gamma ray wavelengths. The centre of the remnant contains a rapidly rotating (30 times per second) neutron star or pulsar that is apparently pumping enormous amounts of energy into the nebula in the form of high-energy particles and magnetic fields. Chandra's X-ray image provides significant clues to the workings of this mighty cosmic 'generator', which is producing energy at the rate of 100,000 suns. The dramatic tilted rings that span the distance of a light year appear to have been flung outward from the pulsar. Perpendicular to the rings, jet-like structures produced by high-energy particles blast away from the pulsar. With Chandra's fine resolution, X-ray jets can be traced all the way in to the neutron star, and an inner ring is seen for the first time. This ring is thought to represent a shock wave due to matter rushing away from the neutron star. A similar, but more focused, flow at the neutron star's polar region produces a jet of particles that blasts away at near the speed of light.

Figure 4. The Crab Nebula.

Apart from the examples shown above, Chandra has sent other equally dramatic X-ray pictures of many other supernova remnants, not only in our own galaxy but also in our neighbouring galaxies like the Small Magellanic Cloud and the Large Magellanic Cloud. Detailed analysis and understanding of these data are still continuing. Meanwhile, Chandra has created history by detecting X-rays from new explosions of stars going on in other galaxies. On November 1 and 2, and 11 and 12, 1999 in two separate observations that lasted approximately nine hours each, Chandra captured a rare glimpse of X-rays from the early phases of a supernova. The supernova was first seen by optical observers on October 29 – just a day or two after the explosion! Named as SN1999em, the supernova was detected in NGC 1637, a spiral galaxy that is 25 million light years from earth. *Figure* 5 shows

With Chandra's fine resolution, X-ray jets can be traced all the way in to the neutron star, and an inner ring is seen for the first time.

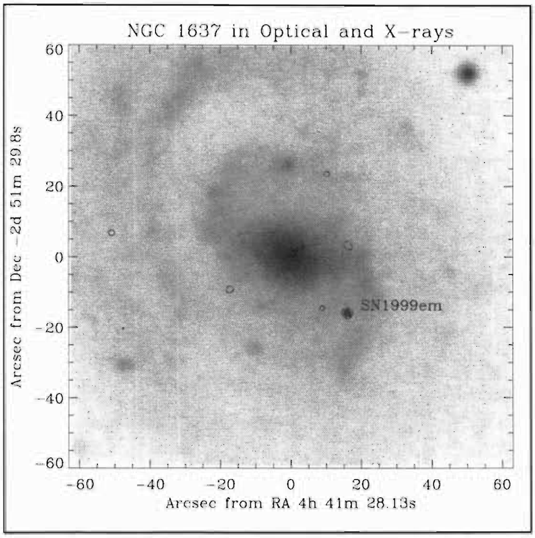


Figure 5.

X-rays by contours overlaid on an optical image. X-rays are emitted by 3 million degree hot gas produced by the supernova as the high speed (32 million km per hour) ejected material crashes into matter shed by the former star before the explosion. An X-ray source in the centre of the galaxy is also detected. Although more than a thousand supernovae have been observed by optical astronomers, the early X-ray glow from the explosions has been detected in less than a dozen cases, and even more rarely so soon after the explosion. The total power in X-rays was equivalent to 50,000 suns on November 1–2. Ten days later it was found that the X-rays had faded to half their initial intensity. The optical luminosity, which had the brightness of 200 million suns, had faded somewhat less. No radio emission was detected at any time.

Clusters of Galaxies

As the largest gravitationally bound objects in the universe, clusters of galaxies provide crucial clues for understanding the origin and fate of the universe. Clusters contain hundreds of galaxies and gaseous material hot enough to emit X-rays. The amount of gas is sufficient to make a thousand more galaxies. Early X-ray observations indicated that the gas in the inner regions of many clusters should be cooling and slowly settling into the centre of the cluster to form new galaxies or hundreds of trillions of dim stars. As astronomers began searching for this cool matter, they were puzzled to find that the new galaxies and stars were not detected in sufficient numbers. The X-ray image of one such cluster known as Hydra A, taken with Chandra's ACIS is shown in *Figure* 6. This cluster is 840 million light years from Earth. *Figure* 6 displays for the first time long snake-like strands of 35 million degree gas extending away from the centre of the cluster. These structures show that the inflow of cooling gas is deflected by magnetic fields, and even pushed back into

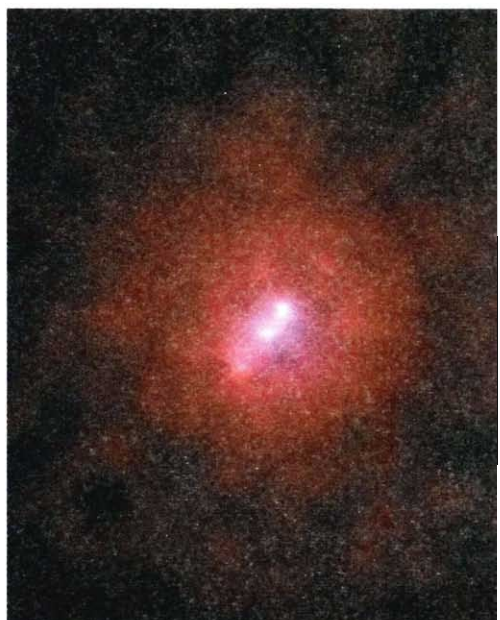
As the largest gravitationally bound objects in the universe, clusters of galaxies provide crucial clues for understanding the origin and fate of the universe.

the cluster by explosions produced close to a central black-hole. The X-ray image also reveals a bright wedge (shown in white) of hot multimillion degree gas pushing into the heart of the cluster. Indeed, combined radio and X-ray observations suggest that a vast bubble of high energy particles is pushing the hot gas aside, creating the Hydra-like loops of hot gas. Like the legendary Hercules who had to contend with the multiple heads of the monstrous Hydra, astrophysicists now know they must deal with the effects of magnetic fields, star formation, rotation, and black-holes if they are to understand what is happening in the inner regions of the galaxy clusters.

Figure 6. Hydra A: A cluster of galaxies in the constellation Hydra.

Chandra has also observed one of the most distant clusters known as 3C295, which is at a redshift of 0.461, which means that we see the galaxy cluster as it was 5 billion years ago. 3C295 was first discovered as a bright source of radio waves that were later found to come from a giant elliptical galaxy located in the centre of the cluster of galaxies. From previous X-ray observations, the cluster is known to be filled with a vast cloud of 50 million degree gas that radiates strongly in X-rays. Astronomers think that the central galaxy has grown over the eons as mass from the colossal gas cloud cooled and settled onto the galaxy. The ACIS instrument on board Chandra has discovered that X-ray emission from this central galaxy is far more complex than previously known (see *Figure* 7). The bright X-ray knots visible for the first time in the Chandra image are probably an indirect result of dumping of gas onto 3C295. The central knot coincides with the centre of the galaxy and these X-rays are most likely due to

Figure 7. X-ray emission from the central galaxy.



X-ray and radio observations indicate that 3C295 was wracked by an awesome explosion that occurred about a million years ago in the centre of the galaxy.

matter falling into a super massive black-hole. The upper and lower knots are in the same location as two large lobes of radio emission. The distance from the top to the bottom knot is about 100,000 light years, comparable to the diameter of our Milky Way galaxy. The radio emission from the knots is understood as due to the synchrotron process (from electrons gyrating in magnetic fields) whereas the X-rays are produced by radio waves being Compton scattered by the high energy electrons.

The total X-ray power in the knots is 3 times greater than all the power produced by our galaxy. X-ray and radio observations indicate that 3C295 was wracked by an awesome explosion that occurred about a million years ago in the centre of the galaxy. Chandra observations suggest that the explosion is related to an excess of matter falling into the massive black-hole. In much the same way that a torrent of water pouring down a drain can produce a back pressure if the flow is more than the drain can handle, the enormous energy released by too much matter flowing into a black-hole could trigger an explosion whereby great quantities of matter and energy would be hurled back into the surrounding gas cloud.

Quasars

Quasars are distant, energetic objects. They are compact intense sources of X-rays as well as visible light, and can be brighter than hundreds of galaxies put together. PKS 0637-752 is one such quasar that is so distant that we see it as it was 6 billion years ago. It is a luminous quasar that radiates with the power of 10 trillion suns from a region smaller than our solar system. This prodigious energy is believed to be produced in the vicinity of a supermassive black-hole. Radio observations of PKS 0637-752 show that it has an extended radio jet that stretches across several hundred thousand light years. Chandra's X-ray image (*Figure* 8) taken with ACIS reveals a powerful X-ray jet of similar size that is probably due to a beam of extremely high-energy particles. The X-ray jet, observed for the first time by Chandra in PKS 0637-752, is a dramatic example of a cosmic jet. It has

PKS 0637-752 is a luminous quasar that radiates with the power of 10 trillion suns from a region smaller than our solar system.

blasted outward from the quasar into intergalactic space for a distance of at least 200,000 light years! The jet's presence means that electromagnetic forces are continually accelerating electrons to extremely high energies over enormous distances. Chandra observations, combined with radio observations, should provide insight into this important cosmic energy conversion process.

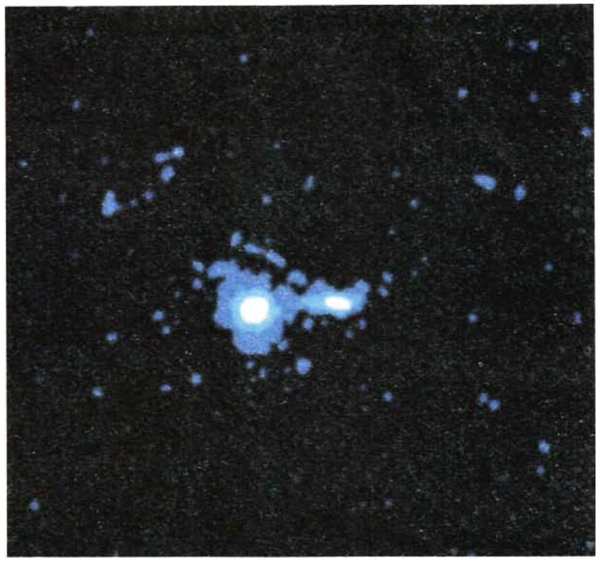


Figure 8. X-ray jet in quasar PKS 0637-752.

High Resolution Spectroscopy

Chandra's revelations of the mysteries of the universe are not just confined to taking super-sharp X-ray pictures shown above. Much more information is expected via high resolution spectroscopy with its gratings. One such example is shown in *Figure* 9. This figure displays the X-ray spectrum of Capella taken with LETG aboard Chandra. Capella is a binary system of two sun-like stars orbiting around each other every 104 days at a distance of about 40 light years from us. Spectroscopy of this quality was previously possible only for the sun and much remains to be understood. Spectra such as this will allow us to study the outer atmospheres (coronae) of sun-like stars by providing key information like densities, temperatures, chemical composition and relative velocities. Similar diagnostic information will also be obtainable for other X-ray sources using the gratings.

Future Directions

As observations go on, Chandra is expected to make a big impact on cosmology. Deep observations will find new gravitational lenses, distant quasars at redshifts greater than 5, and distant clusters of galaxies at redshifts greater than 1. These observations will provide crucial information on the evolution of the universe and its constituents, early ionization history of the universe, and determine the cosmological parameters like den-

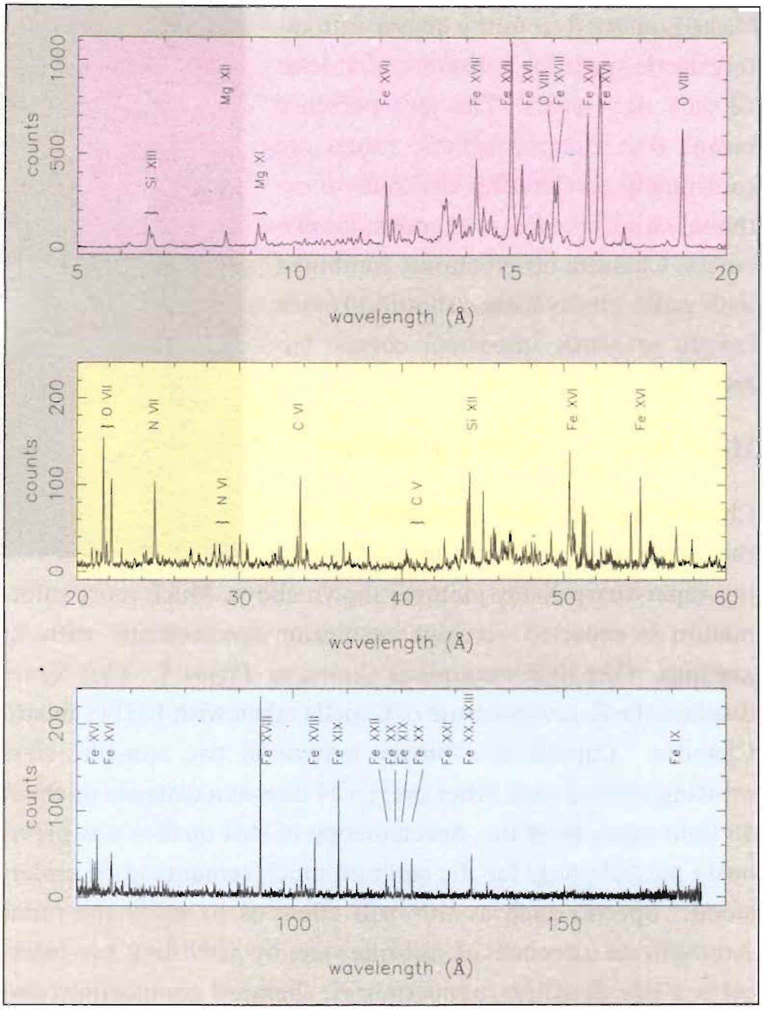


Figure 9. The complete LETGS spectrum of Capella, split into three parts for clarity. Note the difference in x and y scale for the three parts. Indicated in the plot are the triplets discussed in the text and a selection of the Fe lines at longer wavelengths.

sity and distance scale. Long exposures with Chandra may help solve the puzzle about the origin of cosmic X-ray background — one of the most outstanding problems in X-ray astronomy. The CXO will soon have to compete with two new great X-ray observatories. One of these known as XMM (X-ray Multi Mirror) was launched by European Space Agency on 10th December 1999 and is now fully operational. The XMM, renamed as the XMM-Newton after the launch, will have about 4 times more effective area than CXO. Its imaging quality (6 arc secs) is, however, poorer by an order of magnitude. The other one known as ASTRO-E will be launched by Japan in a few years. (Their first attempt in February 2000, failed due to a problem in the rocket). ASTRO-E will have effective area similar to that of CXO but image quality of only about 2 arc mins. ASTRO-E will carry 5 independent telescopes, 4 of which will carry X-ray CCDs, and one will carry a new type of instrument known as a microcalorimeter – a solid state device cooled cryogenically to 60 milli Kelvin. The microcalorimeter works by measuring the temperature difference caused in the crystal lattice (of monolithic etched silicon with implanted thermometer) by the absorption of an X-ray photon. Both XMM-Newton and ASTRO-E are likely to concentrate more on high spectral resolution observations of the type shown in *Figure* 9. The new millennium is truly going to be the *Era of Great X-ray Observatories* for astrophysics and cosmological studies, with Chandra leading the way.

The new millennium is truly going to be the *Era of Great X-ray Observatories* for astrophysics and cosmological studies, with Chandra leading the way.

Suggested Reading

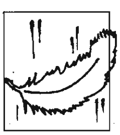
[1] P A Charles and F D Seward, *Exploring the X-ray Universe*, Cambridge University Press, Cambridge, UK, 1995.

[2] W Tucker and R Giacconi, *The X-ray Universe*, Harvard University Press, Cambridge, Massachusetts, 1985.

[3] Web site: http://chandra.harvard.edu/ Chandra X-ray observatory Center operated for NASA by the Smithsonian Astrophysical Observatory (SAO).

Credits for all the pictures: NASA/CXC/SAO

Address for Correspondence
K P Singh
Tata Institute of Fundamental Research,
Mumbai 400 005, India.



The various books and lectures by L Prandtl seem to me to show admirably the way to keep both theory and observation continually in mind, and I have been greatly influenced by them. Prandtl knew in particular the value of a clear photograph of a well-designed experimental flow system, and many of the photographs taken by him are still the best available illustrations of boundary-layer phenomena.

From: An Introdution to Fluid Dynamics
G K Batchelor