The Chandra X-Ray Observatory

The Chandra X-Ray Observatory is the x-ray component of NASA's Great Observatories which also includes the recently decommissioned Compton Gamma Ray Observatory, the Hubble Space Telescope, and the soon to be launched Space Infra Red Telescope Facility. Chandra is a unique x-ray astronomy facility for high-resolution imaging and for high-resolution spectroscopy. Chandra's performance advantage over other x-ray observatories is analogous to that of the Hubble Space Telescope over ground-based observatories.

Chandra is a NASA facility that provides scientific data to the international astronomical community in response to proposals for its use. Data becomes public one year after the observation. The Observatory is the product of the efforts of many commercial, academic, and government organizations in the United States and Europe. NASA's Marshall Space Flight Center (MSFC) manages the Project and provides Project Science; TRW Space and Electronics Group served as prime contractor responsible for providing the spacecraft, the telescope, and assembling and testing the observatory; the Smithsonian Astrophysical Observatory (SAO) provides technical support and is responsible for ground operations.

In 1977, NASA/MSFC and SAO began the study leading to the definition of the then named Advanced X-Ray Astrophysics Facility mission. This study, in turn, had been initiated as a result of an unsolicited proposal submitted to NASA in 1976 by Prof. R. Giacconi (Harvard University and SAO) and Dr. H. Tananbaum (SAO). Several significant events took place during the intervening years including the highest recommendation by the National Academy of Sciences Astronomy Survey Committee, selection of the instruments, selection of the prime contractor, demonstration of the ability to build the optics, restructuring of the mission, selecting the name of the mission in honor of the Nobel Prize winner Subramanyan Chandrasekhar, and the launch.

Chandra was launched July 23, 1999 by the Space Shuttle Columbia. The Commander was Col. Eileen Collins, the first female commander of a Shuttle flight. With a second rocket system, the Inertial Upper Stage (IUS) attached, the Chandra was both the largest and heaviest payload ever deployed from a Space Shuttle. Once deployed, and after separating from the IUS, the Chandra flight system is 13.8-m (43.5-ft) long by 4.2-m (14-ft) diameter, with a 19.5-m (64-ft) solar-panel wingspan. With extensive use of graphite-epoxy structures, the mass of the Chandra flight system is light for its size at 4,800 kg (10,600 pounds).

Following the Shuttle launch and release from the cargo bay, the IUS performed two firings and separated from the Observatory. Finally, after five firings of Chandra's internal propulsion system - the last of which took place 15 days after launch - the Observatory was placed in its highly elliptical orbit. This orbit has an apogee of 140,000 km (1/3 of the way to the moon) and a perigee of 10,000 km. The inclination to the equator is 28.5°. The satellite is above the radiation belts for more than 75% of the 63.5-hour orbital period.

The specified design life of the mission is 5 years; however, the only perishable (gas for maneuvering) is sized to allow operation for more than 10 years. The orbit will be stable for decades.

The first x-rays focused by the telescope were observed on August 12, 1999. Figure 1 shows that image of a young (300 year old) remnant of an exploding star, a supernova remnant, in the constellation Cassiopeia. The Chandra image included a new discovery - the bright visible point near the center of the image was the first detection of the compact star (probably a neutron star) created during the implosion of the more massive progenitor. Discoveries of new astronomical features in Chandra images have been the rule, not the exception.

Figure 1. Chandra image of the supernova remnant Casseopeia-A.

The Chandra optics and detectors provide, for the first time, sub-arcsecond imaging, sub-arcsecond spectrometric imaging, and, together with the transmission gratings, high-resolution x-ray spectroscopy. With these capabilities, a wide variety of high-energy phenomena in a broad range of astronomical objects are being observed. X-rays result from highly energetic processes - thermal processes in plasmas with temperatures of millions of degrees or nonthermal processes, such as synchrotron emission or scattering from very hot or relativistic electrons.

The details of the Observatory are illustrated in Figure 2. The spacecraft is standard except for its lightweight construction and provides pointing control, power, command and data management, thermal control, and other such services to the scientific payload. The principal elements of the payload are the x-ray telescope, the scientific instruments, and the aspect system used to determine where on the sky the observatory was pointed.

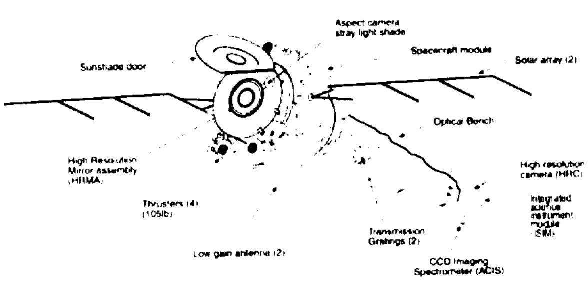

Figure 2. The Chandra X-Ray Observatory.

The telescope is made of four concentric, precision-figured, superpolished Wolter-1 x-ray telescopes, similar to the Einstein Observatory, but of much higher quality, larger diameter, and longer focal length. The Wolter-1 design uses a paraboloid of revolution followed by a hyperboloid of revolution. Two reflections minimize coma. The 4-mirror-pair grazing-incidence optics are constructed of Zerodur, a glassy ceramic chosen for its high thermal stability. The optics are coated with iridium, chosen for high reflectivity at the x-ray energies of interest 0.08 - 10.0-keV (15-0.12 nm).

The aspect camera system includes a visible-light telescope and CCD camera attached to the telescope. A fiducial-light transfer system is used to project lights attached to the focal-plane instruments onto the aspect. Thus, the aspect camera simultaneously determines both where the observatory was pointing and the location of the x-ray detectors relative to the positions of known stars.

The science instrument module includes mechanisms for focusing and translating Chandra's focal-plane instruments. Translation is required as the instruments cannot realistically share the telescope's focus.

Just behind the telescope are 2 objective transmission gratings - the Low-Energy Transmission Grating (LETG) which is optimized for longer x-ray wavelengths and the High-Energy Transmission Grating (HETG) optimized for shorter wavelengths. Positioning mechanisms may insert either grating into the converging beam to disperse the x-radiation onto the focal plane producing high-resolution spectra read-out by one of the detectors. The gratings allow for measurements with spectral resolving power of $\lambda/\Delta\lambda = E/\Delta E > 500$ for wavelengths of > 0.4-nm (energies < 3 keV).

The Space Research Institute of the Netherlands and the Max-Planck-Institut fur Extraterrestrische Physik designed and fabricated the LETG. The assembly is made of 540 grating facets with gold bars of 991-nm period. The LETG provides high-resolution spectroscopy from 0.08 to 2 keV (15 to 0.6 nm).

The Massachusetts Institute of Technology (MIT) designed and fabricated the High-Energy Transmission Grating (HETG). The HETG uses 2 types of grating facets - the Medium-Energy Gratings (MEG) which, when inserted, are placed behind the telescope's 2 outermost shells, and the High-Energy Gratings (HEG), behind the 2 innermost shells. The HEG and MEG are oriented at slightly different dispersion directions. With polyimide-supported gold bars of 400-nm and 200-nm periods, the HETG provides high-resolution spectroscopy from 0.4 to 4 keV (MEG, 3 to 0.3 nm) and from 0.8 to 8 keV (HEG, 1.5 to 0.15 nm).

Chandra's 2 focal-plane science instruments are the High Resolution Camera (HRC) and the Advanced CCD Imaging Spectrometer (ACIS).

SAO designed and fabricated the HRC. One of the HRC detectors is made of a 10-cm-square microchannel plate, and provides high-resolution imaging over a 31-arcmin-square field of view. A second detector, comprising 3 rectangular segments (3-cm-by-10-cm each) mounted end-to-end along the grating dispersion direction, serves as the primary read-out detector for the LETG. Both of the HRC detectors are coated with a cesium-iodide photocathode and have thin aluminized polyimide shields to prevent contamination by ions and ultraviolet light.

The Pennsylvania State University MIT built the ACIS with charge-coupled devices (CCDs) fabricated by MIT's Lincoln Laboratory. As with the HRC, there are two detector systems. One is made of a 2-by-2 array of CCDs, and provides high-resolution spectrometric imaging over a 17-arcmin-square field of view. The other, a 6-by-1 array mounted along the grating dispersion direction, serves as the primary read-out detector for the HETG. Two types of CCDs were used, 8 front-illuminated (FI) and two back-illuminated (BI). The latter CCDs have higher efficiency at lower energies than the FI devices, but were much more difficult to fabricate. One BI was placed at the on-axis focal position of the 6 x 1 array. Thus this particular CCD also provides high-resolution spectrometric imaging extending to lower energies, but over a smaller (8-arcmin-square) field than the 2 x 2 array. Both ACIS detector systems have thin aluminized polyimide filters to minimize contamination by visible light.

The Observatory's point spread function, as measured during ground calibration, had a full width at half-maximum less than 0.5 arcsec and a half-power diameter less than 1 arcsec. The prediction for the on-orbit encircled-energy fraction was that a 1-arcsec-diameter circle would enclose at least half the flux from a point source. The relatively mild dependence on energy, resulting from diffractive scattering by surface microroughness, attested to the excellent superpolished finish of the Chandra optics, less than about 3 angstroms rms. The ground measurements were, of course, taken under environmental conditions quite different than those encountered on-orbit. Most notably the effects of gravity on the optics and the finite distance and the size of the various x-ray sources used were unique to the ground calibration. On the other hand, on the ground there was no Observatory motion to deal with. On-orbit the performance includes the spatial resolution of the flight detectors and any uncertainties in the aspect solution. The on-orbit performance met expectations.

Chandra's capability for high-resolution imaging enables detailed high-resolution studies of the structure of extended x-ray sources, including supernova remnants, astrophysical jets, and hot gas in galaxies and clusters of galaxies. The additional capability for spectrometric imaging allows studies of structure, not only in x-ray intensity, but also in temperature and in chemical composition. Through these observations, astronomers are addressing several of the most exciting topics in contemporary astrophysics; e.g., galaxy mergers, dark matter, and the cosmological distance scale.

In addition to mapping the structure of extended sources, the high angular resolution permits studies of ensembles of discrete sources, which would otherwise be impossible. An example comes is the Chandra observation of the center of Andromeda (M31)- Figure 3. The image shows what used to be considered as the emission associated with the black hole at the center of the galaxy now resolved into several objects. A most interesting consequence was that the emission from the central black hole is unexpectedly and surprisingly faint. Chandra observations are being used to isolate individual stars in clusters and star-forming regions and x-ray binaries in nearby normal galaxies. Furthermore, high-angular-resolution observations with Chandra are obtaining deep-field exposures likely to resolve most of the extragalactic cosmic x-ray background into faint, discrete sources.

Figure 3. Chandra image of the center of Andromeda (M31). The central region is resolved into 5 distinct sources, the faintest and coolest of which is shown in blue and is associated with the black hole at the center of the galaxy.

Equally important to the imaging science will be Chandra's unique contributions to high-resolution dispersive spectroscopy. As the capability for visible-light spectroscopy begat the field of astrophysics about a century ago, high-resolution x-ray spectroscopy will contribute profoundly to the understanding of the physical processes in cosmic x-ray sources. High-resolution x-ray spectroscopy is the essential tool for diagnosing conditions in hot plasmas. It provides information for determining temperature, density, elemental abundance, and the ionization stage of x-ray emitting plasma. The high spectral resolution of Chandra isolates individual lines from the myriad of spectral lines, which would overlap at lower resolution and it enables the determination of flow and turbulent velocities, through measurement of Doppler shifts and line-widths.