The Advanced X-ray Astrophysics Facility (AXAF)

Martin C. Weisskopf and Stephen L. O'Dell
NASA, Marshall Space Flight Center
and
Leon Van Speybroeck
Smithsonian Astrophysical Observatory

ABSTRACT

AXAF is an x-ray observatory designed to study x-ray emission from all categories of astronomical objects — from normal stars to quasars. AXAF has broad scientific objectives and outstanding capability to provide high resolution (< 1-arcsec) images, spectrometric imaging and high resolution dispersive spectroscopy over the energy bandwidth from 0.1 to 10-keV.

This is a significant year in the development of AXAF, to be launched in late 1998. Major elements of the observatory — the optics and the scientific instruments — are now nearing completion in preparation for calibration later this year.

2. INTRODUCTION

NASA's Marshall Space Flight Center manages the AXAF Project, with scientific and technical support from the Smithsonian Astrophysical Observatory. TRW's Space and Electronics Group is the prime contractor and provides overall systems engineering and integration. The following major subcontracts relate directly to the optics: Hughes Danbury Optical Systems built the x-ray optics; Optical Coating Laboratory coated the optics with sputtered iridium; and Eastman Kodak Company is mounting and aligning the optics and providing the optical bench. Other optical systems on AXAF include a CCD visible-light imaging aspect camera, to record star images and provide data for determining where the Observatory was pointed. Ball Aerospace & Technologies is responsible for this aspect camera system. The scientific instruments comprise two sets of objective transmission gratings, that can be inserted just behind the x-ray optics, and two sets of focal-plane imaging detectors.

The fully deployed AXAF, shown schematically in Figure 1, is 13.8-m (45.3-ft) long, with a 19.5-m (64-ft) solar-array wingspan and has a 4500-kg (5-ton) on-orbit mass. AXAF will be placed in a highly elliptical orbit, with a 140,000-km apogee and 10,000-km perigee, by means of the Space Shuttle, Boeing's Inertial Upper Stage, and AXAF's internal propulsion system.

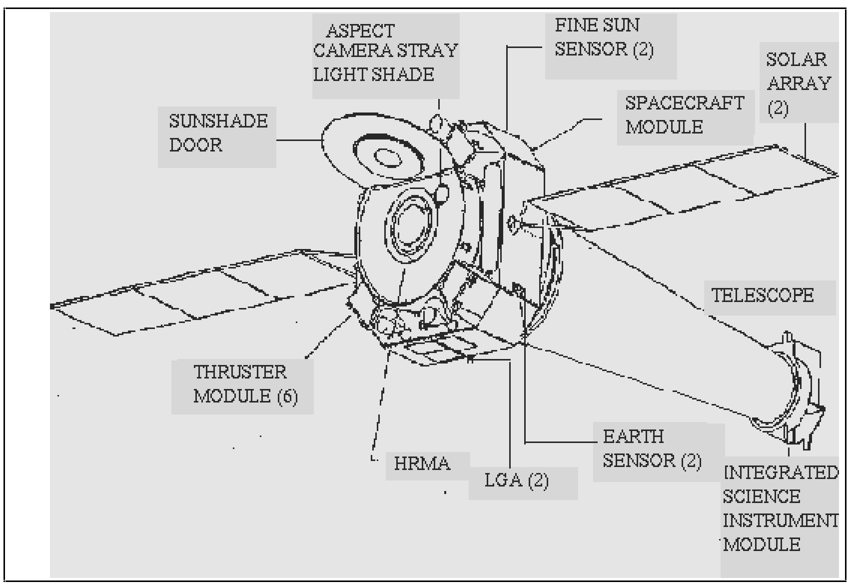

Figure 1. Schematic representation of AXAF showing the major elements of the observatory.

3. THE X-RAY OPTICS

The heart of the observatory is the x-ray telescope comprising four paraboloid/hyperboloid pairs, which have a common ten meter focal length, element lengths of about 0.83-m, diameters of approximately 0.63, 0.85, 0.97, and 1.2 m, and wall thickness between about 16-mm for the smaller elements and 24-mm for the outer. Zerodur from Schott was selected for the optical element material because of its low coefficient of thermal expansion and previously demonstrated capability of permitting very smooth polished surfaces.

Hughes Danbury Optical Systems (HDOS) manufactured the mirror elements. The major fabrication phases included coarse and fine grinding, polishing, and the final smoothing. The grinding and polishing operations were done with relatively small tools under computer control. The cycle was iterative: After a mirror element was measured to yield an error map, appropriate small tools were selected to reduce the errors, a polishing control file for the next cycle would be generated to remove more material in the high areas. The residual errors ere then smaller than the original, so that the process converged to the required accuracy.

Three principal metrology instruments were used at HDOS for fabrication and final acceptance data. Axial figure errors at fixed azimuthal angles were measured in the Precision Metrology Station (PMS), by interferometrically determining the separation between the optical surface and a calibrated reference surface. A Circularity and Inner Diameter Station (CIDS), used to determine the inner diameters and roundness errors near the ends of the mirrors, included two pairs of opposed contacting radial probes, calibrated reference bars, positioning mechanisms, and a precise air bearing to permit rotation. The instruments were housed in environmentally controlled enclosures, and the mirror elements were carefully supported in the vertical orientation to achieve the required accuracy. The Micro-Phase Measuring Interferometer (MPMI), an adaptation of a WYKO instrument, was used to obtain high-frequency roughness measurements for small samples of the mirror surfaces. The x-ray performance is more sensitive to high-frequency than to low-frequency errors, and to axial than to circumferential errors: This is reflected in the accuracy of each instrument — namely, about 0.5, 20, and 200-Å-rms for the MPMI, PMS, and CIDS, respectively. Numerous cross-checks, such as comparisons with data from other (but less accurate) instruments and data from different orientations, were performed to avoid serious undetected systematic errors. The data reduction itself was a substantial effort: For example, the final data set, including both raw and processed data, consists of more than 40,000 computer files. The impending x-ray calibration will provide another very important check of the optical performance.

The PMS axial data and CIDS circumferential data were combined to yield low-frequency surface error maps; these errors were reduced to an average of 50-Å-rms for the axial component by computer controlled polishing with small tools. This typically required four grinding and four polishing cycles per element, which is extremely rapid convergence by traditional optical shop experience. Figure 2 shows the largest optical element being ground at HDOS. Aluminum rings (visible in the Figure 2), which provided support to the optics during the abrasive material removal process, were removed during measurements so that an essentially stress-free shape could be determined. Heater elements on the rings were used to facilitate glass insertion or removal through differential expansion of the glass and support structure. The final polishing was performed with a large lap designed to reduce surface roughness without introducing unacceptable lower frequency figure errors. The resulting rms surface roughness over the central 90% of the elements varied between 1.85 and 3.44 Å in the 1 to 100 mm^{-1} band: This excellent surface smoothness enhances the encircled-energy performance at higher energies. The expected performance of the mirrors exceeds the contractual specifications and goals at essentially all energies. HDOS completed fabrication of the eight AXAF optical elements about four months ahead of schedule.

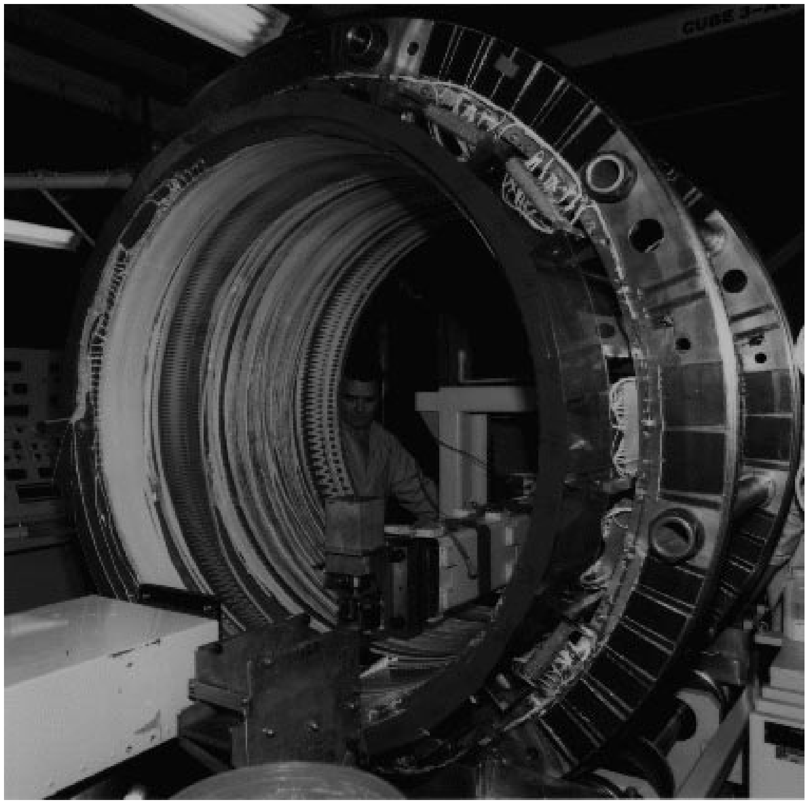

Figure 2. The largest AXAF paraboloid is shown being ground under computer control at Hughes Danbury Optical Systems. The aluminum support rings were used during grinding and polishing, but were removed during metrology.

The mirror elements then were coated at Optical Coating Laboratories, Inc. (OCLI) by sputtering with iridium over a chromium binding layer. OCLI performed verification runs with surrogates before each coating of flight glass; these surrogates included optical witness samples which were used to show that coating thickness would be uniform and that the surface smoothness would not be degraded. The x-ray reflectivities of the witness flats also were measured at SAO to ascertain that the expected densities were being achieved. Similar tests on witness samples coated at the same time as the flight optics indicate that the coatings should provide better than the specified performance and result in very little if any degradation of the surface smoothness. The last planned cleaning of the mirrors occurred at OCLI prior to coating, and stringent contamination controls were begun at that time. Figure-3 shows the smallest paraboloid in the OCLI handling fixture after being coated.

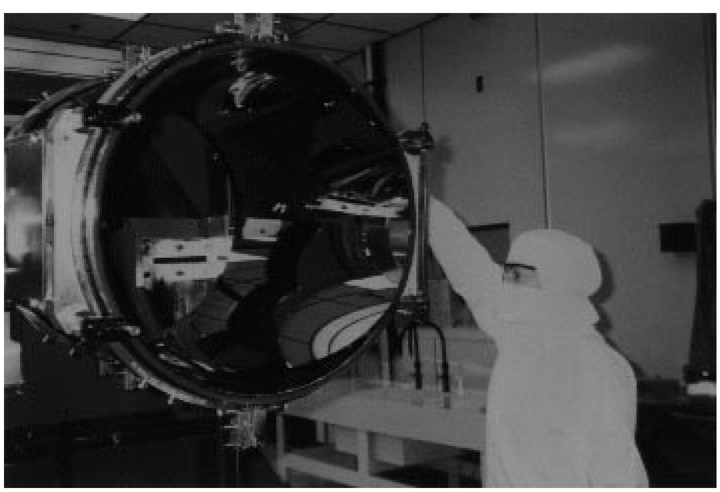

Figure 3. The smallest AXAF paraboloid is shown in its handling fixture after being coated with iridium at Optical Coating Laboratories, Inc.

The Eastman Kodak Company (EKC) is currently accomplishing final alignment and assembly of the mirror elements into the High-Resolution Mirror Assembly (HRMA). Figure 4 shows the completed mirror-element support structure, which was designed by EKC. Each mirror element will be bonded near its mid-station, to flexures previously attached to the carbon-fiber composite mirror support sleeves. The four support sleeves and associated flexures for the paraboloids appear near the top of the figure, and those for the outer hyperboloid appear at the other end. The inner support cylinder, protruding near the top, will support x-ray and thermal-control apertures to be added later. Some thermal control heaters are visible around the periphery of the structure. The flexures effect only small radial forces on the mirrors and, therefore, reduce the support-induced axial-slope errors to which mirror performance is especially sensitive. The thin mirror shells are susceptible to a deformation mode in which both ends become oval, but with perpendicular major axes; supporting the mirror elements near their centers minimizes the coupling of support errors into this mode. The final mirror alignment is performed, with the optical axis vertical, in a clean and environmentally controlled tower. The mirror elements are supported to approximate the gravity and stress-free state, positioned mechanically and optically, and then bonded to the flexures described previously. The Bauer Associates optical instrument used for alignment, generates a laser beam which passes through the x-ray optics, is reflected from an auto-collimating flat, and returns through the x-ray optics to the instrument. The variation of the returned spot position with azimuth provides the information required to position the x-ray optical elements. After the x-ray elements are assembled, EKC will add outer support cylinders, the remainder of the thermal control system, contamination covers, and components of the flight alignment system.

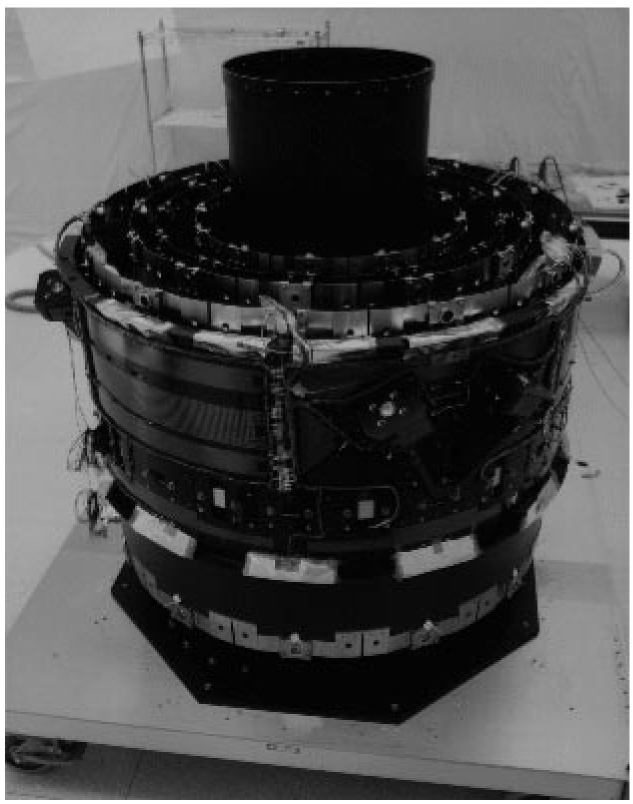

Figure 4. The mirror support structure, designed by the Eastman Kodak Corporation, supports the AXAF mirror elements near their centers with radially compliant flexures attached to carbon-fiber composite support sleeves. The inner support cylinder and some of the thermal control heaters also can be seen.

The HRMA will be taken to NASA's Marshall Space Flight Center (MSFC) for final x-ray calibration, in the fall of this year, and then to TRW for integration into the spacecraft. The largest mirror pair was x-ray tested, prior to coating, during the development program and showed a measured angular resolution of 0.22 arcsec (FWHM). The AXAF mirrors are the largest high-resolution x-ray optics ever made. Figure 5 (left panel) shows the AXAF effective area as a function of energy, along with those of its Einstein and ROSAT predecessors. The AXAF mirror areas are about four times greater than the Einstein mirrors. The effective areas of AXAF and ROSAT are comparable at lower energies because the somewhat smaller ROSAT mirrors have larger grazing angles; however, the smaller grazing angles of AXAF yield much greater throughput at higher energies. Figure 5 (right panel) shows the fraction of the incident flux at 1.49 keV, included in the core of the expected AXAF response, as a function of image radius and analogous data for the Einstein and ROSAT mirrors. The excellent agreement, between predictions and subsequent x-ray measurements taken for previous mirrors as part of the AXAF program, validates the methodology for predicting x-ray performance based upon optical and mechanical metrology. The expected improvement within 0.5 arcsec is dramatic, although it is important to note that the ROSAT mirrors exceeded their specification and were well matched to the principal detector for that mission. The excellent surface smoothness achieved for the AXAF and ROSAT mirrors result in a very modest variation of the performance as a function of energy: This will reduce uncertainties which accrue from using calibration data to infer properties of sources with different spectra, and will improve the precision of the many quantitative experiments to be performed with the AXAF.

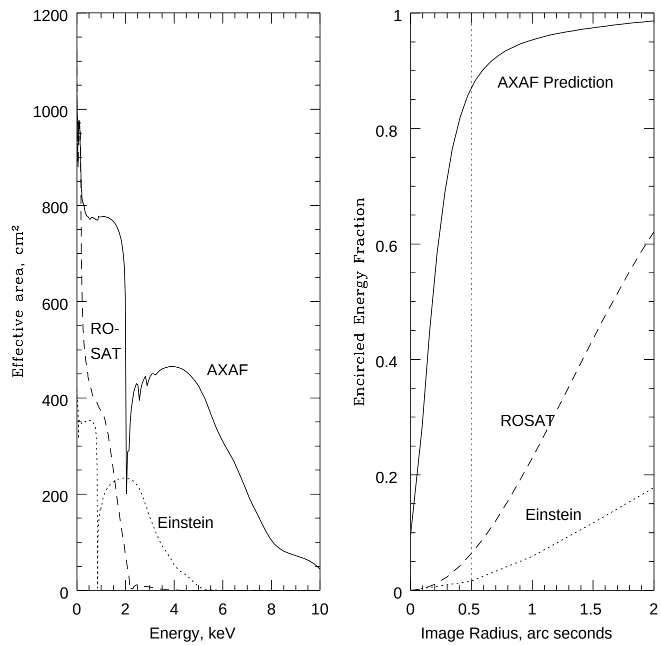

Figure 5. The effective areas (left panel) of the AXAF, Einstein, and ROSAT mirrors as a function of energy. AXAF has significantly more area over a wider bandwidth than its predecessors. The expected fraction (right panel) of the effective area included within the AXAF image as a function of radius is shown for 1.49-keV x rays. The responses for the Einstein and ROSAT mirrors also are shown, although neither was specified for these small angles and ROSAT exceeded its specification. The improvement within 0.5 arcsec is dramatic.

4. THE SCIENTIFIC INSTRUMENTS

AXAF has two focal-plane instruments — the High-Resolution Camera (HRC) and the AXAF CCD Imaging Spectrometer (ACIS). Each of these instruments, in turn, has two detectors, one for direct imaging of x rays that pass through the optics and the other for imaging x rays that are dispersed by the objective transmission gratings, when the latter are inserted directly behind the HRMA. Each focal-plane detector operates in essentially the photon-counting mode and has very low internal background.

The Smithsonian Astrophysical Observatory, with Dr. S. Murray the Principal Investigator, is producing the HRC. The imaging detector (HRC-I) is a large-format, 100-mm (4-in) square microchannel plate, coated with a cesium iodide photocathode to improve x-ray response. A conventional cross-grid charge detector reads out the photo-induced charge cloud: the electronics determine the arrival time (to 16-μs) and the position with a resolution of about 18 μm corresponding to 0.37 arcsec. The spectroscopy readout detector (HRC-S) is a 300-mm × 20-mm, 3-section, microchannel plate. Sectioning allows the 2 outside sections to be tilted in order to conform more closely to the Rowland circle that includes the objective transmission gratings.

The ACIS has two charge coupled-device (CCD) detector arrays — ACIS-I for high resolution spectrometric imaging and ACIS-S for readout of the high-energy transmission gratings. Prof. G. Garmire of the Pennsylvania State University is the

Principal Investigator. The Massachusetts Institute of Technology's Center for Space Research, in collaboration with Lincoln Laboratories, is developing the detector system and manufacturing the CCDs. Baffles and an optical blocking filter (1500-Å aluminum on 1000-Å Lexan) shield against visible light. The imaging array is a 2×2 array of CCDs. The 4 CCDs tilt slightly toward the optics to conform more closely to the focal surface. Each CCD has 1024×1024 pixel of 24-μm (0.5-arcsec) size. The primary use of this array is for spectrometric imaging. The ACIS spectroscopy readout has a 1×6 array, tilted slightly to conform to the Rowland circle. It incorporates both front and back-illuminated CCDs, the later being more sensitive to the lower energy x rays.

Both sets of objective transmission gratings contain hundreds of individual co-aligned facets mounted to supporting structures on 4 annuli (one for each of the four co-aligned telescopes), to intercept and disperse x rays exiting the HRMA. In order to optimize energy resolution, the grating support structure holds the facets close to the Rowland toroid that intercepts the focal plane.

The Low-Energy Transmission Grating (LETG) will provide high-resolution spectroscopy at the lower end of the AXAF energy range. Dr. A Brinkman, of the Space Research Organization of the Netherlands, is the Principal Investigator. The LETG is being developed in collaboration with the Max Planck Institut für Extraterrestische Physik. The LETG has 540 1.6-cm (0.63-in) diameter grating facets, 3 per grating module. Ultraviolet contact lithography is used to produce an integrated all-gold facet which is bonded to a stainless-steel facet ring. An individual facet has 0.43-μm-thick gold grating bars with 50% filling factor and 9920-Å period, resulting in 1.15-Å/mm dispersion. The HRC-S is the primary readout device for the LETG.

The High-Energy Transmission Grating (HETG) will provide high-resolution spectroscopy at the higher end of the AXAF energy range. Prof. C. Canizares of the Massachusetts Institute of Technology Center for Space Research, is the Principal Investigator. This group is developing the instrument in collaboration with MIT's Nanostructures Laboratory. The HETG has 336 2.5-cm (1.0-in) square grating facets. Microlithographic fabrication, using laser interference patterns, is used to produce the facets, which consist of gold grating bars with 50% filling factor on a polyimide substrate. The HETG uses gratings with 2 different periods which are aligned to slightly different dispersion directions, forming a shallow "X" image on the readout detector. The Medium-Energy Gratings (MEG) have 0.40-μm-thick gold bars on 0.50-μm-thick polyimide with 4000-Å period producing 2.85-Å/mm dispersion, and are placed behind the outer two AXAF mirrors. The High Energy Gratings (HEG), placed behind the inner two AXAF mirrors, are 0.70-μm-thick-gold bars on 1.0-μm-thick polyimide with 2000-Å period, resulting in 5.7-Å/mm dispersion. The ACIS-S is the primary readout for the HETG.

Figure 6 summarizes the expected spectroscopic performance of AXAF, to be calibrated at the end of this year at Marshall Space Flight Center's X-Ray Calibration Facility (XRCF).

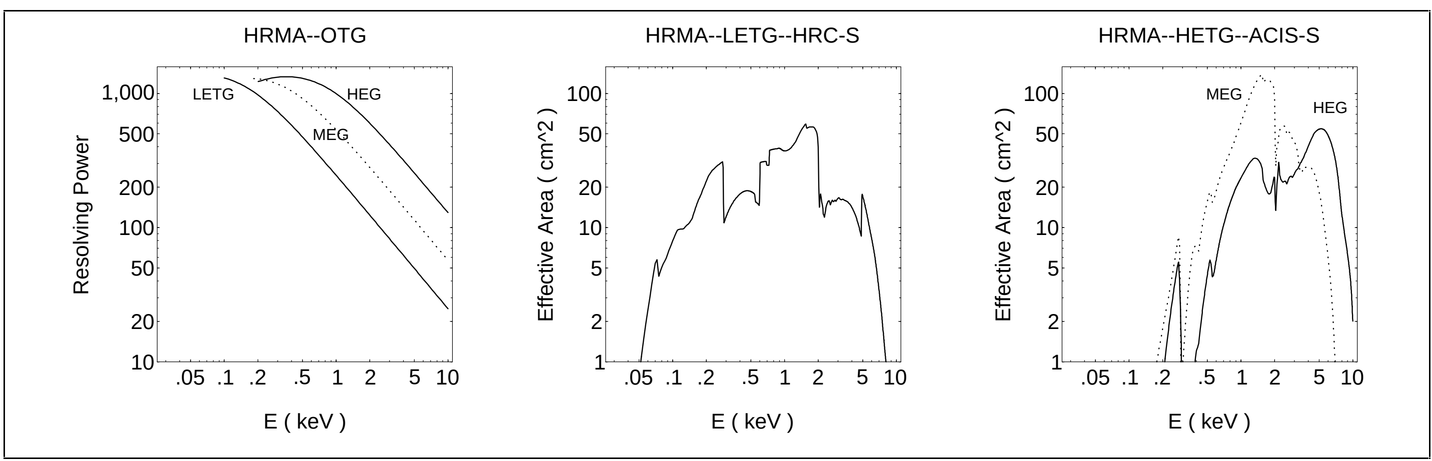

Figure 6. Expected spectroscopic performance of AXAF. The left panel shows the approximate resolving power. The central panel displays the effective area of the LETG spectrometer with the HRC-S readout. The right panel shows the effective area for the HETG spectrometers with the ACIS-S readout (assuming only front illuminated CCDs).