Thin Shell, Segmented X-ray Mirrors

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Abstract

Thin foil mirrors were introduced as a means of achieving high throughput in an X-ray astronomical imaging system in applications for which high angular resolution were not necessary. Since their introduction, their high filling factor, modest mass, relative ease of construction, and modest cost have led to their use in numerous X-ray observatories, including the Broad Band X-ray Telescope, ASCA, and Suzaku. The introduction of key innovations, including epoxy replicated surfaces, multilayer coatings, and glass mirror substrates, has led to performance improvements, and in their becoming widely used for X-ray astronomical imaging at energies above 10 keV. The use of glass substrates has also led to substantial improvement in angular resolution, and thus their incorporation into the NASA concept for the International X-ray Observatory with a planned 3 m diameter aperture. This paper traces the development of foil mirrors from their inception in the 1970's through their current and anticipated future applications.

Introduction

The thin foil X-ray mirror was invented to fulfill a particular observational objective. In the 1970's, with the introduction into X-ray astronomy of high resolution imaging through the Wolter I mirrors on the Einstein Observatory, it became recognized that not all applications for which imaging is desired require high angular resolution (<1 arcmin). High angular resolution comes at a cost: mirrors must be accurately figured and held rigidly. These requirements lead to a thick substrate, high mass, and large expense. Since X-ray imaging above ~0.02 keV requires grazing incidence mirrors, the need for thick substrate material leads to inefficient aperture utilization (i.e., low throughput), and thus limited sensitivity. For some astronomical measurements it is desirable to take advantage of the increased sensitivity afforded by imaging but where high throughput is preferred over angular resolution. This is especially true in situations in which the detection of a large numbers of photons is required to perform the measurement of interest; examples include spectroscopy of relatively isolated sources and polarimetry. For such applications, replacing a small number of thick, massive, expensive mirror shells with a large number of thin, low mass, low cost shells offers the desired improvement in throughput with sufficient angular resolution to resolve most sources. Thus the driving idea behind the foil mirror was to provide a low cost, low mass, high throughput alternative to high-resolution mirrors.

the next shell outward: viewing from the front of the mirror on axis, the entire aperture is covered by either a reflecting surface or the front edge of one. This maximum filling approach leads to a linear off-axis vignetting function. The vignetting with off-axis angle is a function of incident energy, steeper at higher energy. A practical approximation of the diameter of the field of view is given by the average graze angle of the mirror. At radii beyond half the graze angle, the effective area is typically less than half the on-axis area. The angular resolution, if characterized by half power diameter (HPD), is essentially constant across the field of view: off axis aberrations are small compared with the blur introduced by the conical approximation within the field of view of a typical focal plane instrument. The image of a point source changes from circularly symmetric to elongated perpendicular to the off axis shift direction, however. Outside the nominal field of view, aberrations (particularly coma and oblique spherical aberrations) degrade the HPD.

The conical design has several practical attributes that simplify construction. First, it can be shown by simple geometric arguments that all the many nested mirror surfaces in each of the two reflection stages (paraboloid analog, usually referred to as the primary surface; and hyperboloid analog, referred to as the secondary), when flattened onto a plane, all describe a segment of the same annulus. This means that the substrates can be mass produced, with only two cutting fixtures needed to shape substrates. Second, since no axial curvature is imparted to the reflecting surfaces, surface preparation can be kept simple (e.g., forming the overall shape of a relatively smooth substrate). The only requirement on the preparation technique is that it produce or preserve a surface that is smooth on spatial scales larger than approximately 1 mm. Various coating techniques can then provide the necessary smoothness on smaller spatial scales. Third, the design lends itself to modularity and mass production. The mirror is usually divided into angular segments, quadrants or thirds, with a separate housing for each.

The introduction of the conical approximation greatly reduces the precision requirements on the substrate. A number of substrate materials have been tried, but the best-suited material is aluminum. Aluminum has low density, the right balance between stiffness and ductility to allow forming, and can be found in large, thin rolls or sheets with high gloss finish.

The method used for shaping aluminum into the conical form has changed minimally since its first use. If the raw stock comes from a roll, it was first flattened by compression between two glass plates under heat. The aluminum is cut approximately to shape and then given its basic shape (a segment of a cone frustum) by pressing it against a mandrel and thermally cycling it. The aluminum is formed so that global surface structure such as roll marks runs along the direction of incidence of the radiation to minimize scatter off surface features that remain after coating. (This means that stock from a roll needs to be flattened so that curvature can be introduced in the opposite direction.) Refinements in this process include the mandrel shape (originally cylindrical, now conical, and with increasing radial accuracy), how the substrates are held against mandrels (originally mechanically and now using suction), and the details of the thermal cycle used for the forming.

Mounting in a housing and aligning 100 or more pairs of mirror segments is challenging, and misalignment remains a primary source of blur. Serlemitsos [2] introduced gang alignment, whereby all of the segments in the primary or secondary housing are loaded together, and are held in place front and rear by a set of accurately grooved radial alignment bars. Substantial research has gone into optimizing the number of alignment bars as well as the shape of the grooves. The grooves must be precisely located and not allow the segments to shift. At the same time they cannot be so narrow as to prevent insertion of segments or to distort them. A housing and a magnified portion of an alignment bar are shown in Figure 3.
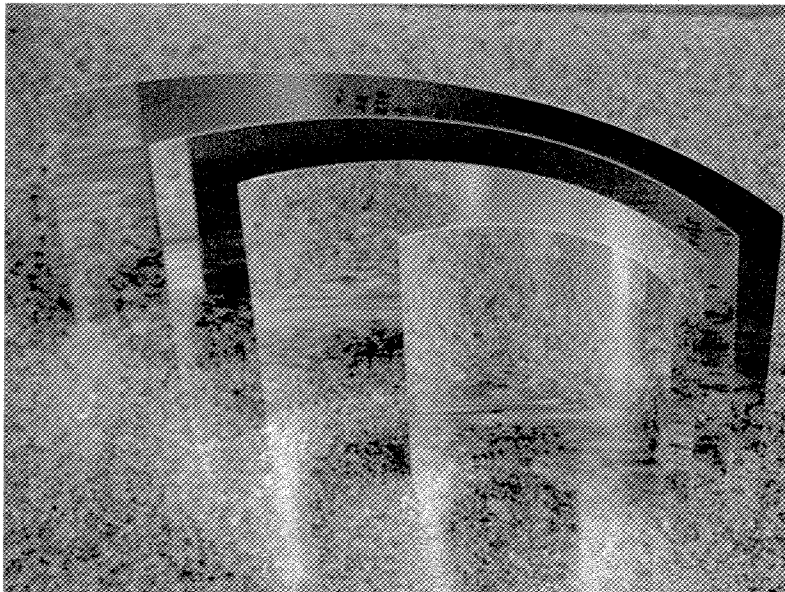

Figure 2: Finished foil mirror segments. These particular mirror segments were produced using epoxy replication, but appear identical to those produced using laquer coating.

Gang alignment offers the substantial benefit that it can be done relatively quickly (Figure 4). Its primary disadvantage is the limit it places on angular resolution – aligning all the segments to the best average focus introduces segment-to-segment variation. The need for the grooves to be wider than the segments to allow loading without damaging the segments and introducing distortions leads to the introduction a small variation in mirror slope is introduced, in turn leading to blur. This slope error tends to be random within a quadrant, and is typically an arc minute in the mirrors developed for flight.

Primary to secondary alignment is generally performed in an optical beam, while the location of the focus and quality of the image is monitored. Figure 5 shows a completed module, in this instance a quadrant. Once all the modules comprising a mirror (primary plus secondary) have been populated and internally aligned, they are mounted on a ring.
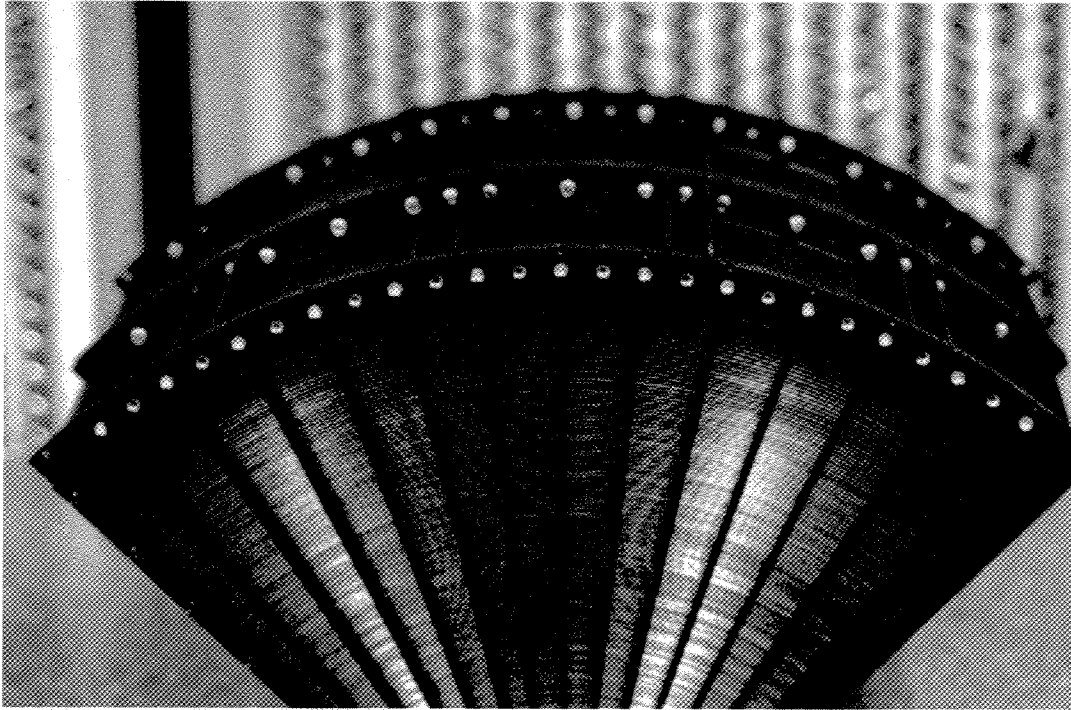
Figure 5: A completed quadrant, viewed from the front.

The first foil mirrors

A total of eight flight quality lacquer coated foil mirrors were produced at GSFC between 1987 and 1992. The parameters of these mirrors are summarized in Table 1. One of these was for a sounding rocket instrument, two for the Broad Band X-ray Telescope (BBXRT) and five for the Japan/US X-ray observatory ASCA (four flight plus one spare). The properties of these mirrors are listed in Table 1.

The first conical mirror to fly was constructed in 1987 for a Supernova X-ray Spectrometer sounding rocket payload, intended to search for X-ray emission from SN 1987A [2]. The mirror was adopted from the (not yet built) BBXRT design, but the focal length was reduced from 3.84 m to 2.1 m. It was launched in February 1988 with a pixilated Si(Li) detector at its focus. During its five-minute exposure above the atmosphere, it detected LMC X-1 as well as hot, diffuse emission from the LMC, but not SN 1987A, which it failed to observe due to an attitude control program error. The mirror was recovered intact. Its primary success was a demonstration that such mirrors can survive a launch environment, and deliver the expected performance in space. This mirror has recently been renovated and will be used on the Micro-X sounding rocket instrument [4].

observed; this was ascribed to residual roughness of the mirror foils. The degree of energy dependence was not quantified, but consistent with that measured for the mirrors on ASCA, which were fabricated using the same approach (see below). The effective area of each mirror was approximately 290 cm^2 at 1 keV and 125 cm^2 at 7 keV.

The Japanese-US ASCA was the first free flying, general use X-ray observatory to incorporate foil mirrors [6]. With its foil mirrors and its groundbreaking CCD detectors, ASCA made numerous important contributions to astrophysics, and demonstrated the utility of both high throughput mirrors and CCD detectors.

ASCA was severely mass limited, with a total mass of ~400 kg. Thus there was a premium on the effective area-to-mass ratio of the X-ray mirrors, a situation for which foil mirrors provide the best solution. ASCA incorporated four identical coaligned foil mirrors, each with a mass of 10 kg [7]. Two mirrors illuminated imaging gas scintillation proportional counters, the other two illuminated the first CCD detectors ever used in an orbiting X-ray observatory. Each mirror had a diameter of 35 cm and a 3.5 m focal length and consisted of 120 nested shells. The foil thickness and axial length were the same as in BBXRT. Also as in BBXRT, the mirror surfaces were produced using the lacquer coating, with an evaporated gold overcoat. One of the flight mirrors is shown in Figure 6.
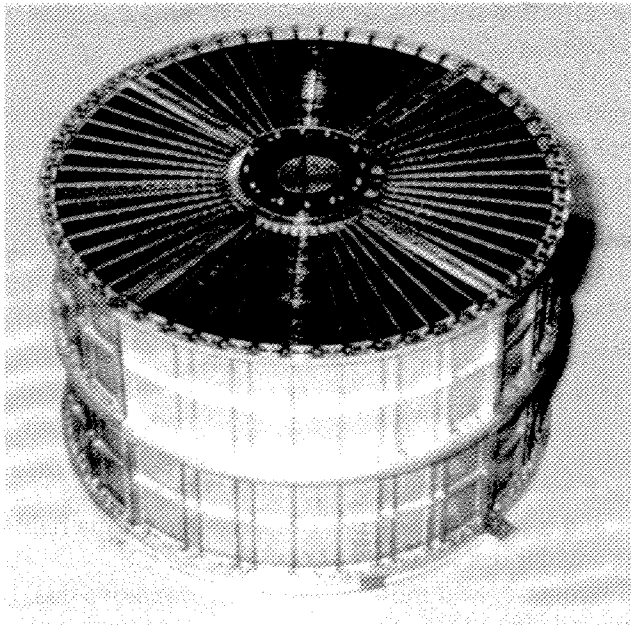

Figure 6: An ASCA flight mirror, one of five constructed. The aperture diameter is 35 cm; the height is approximately 20 cm. The mirror consists of 118 nested shells and has a mass of 10 kg.

produce better quality mirror surfaces than lacquer coating and lend itself to mass production.

The replication process introduced by Serlemitsos & Soong [11] does just that. First, the thin reflective layer (gold or platinum) is deposited onto a glass mandrel. Then a thin, even layer of epoxy is sprayed onto the preformed aluminum substrate and/or the coated mandrel. The mandrel and substrate are brought into contact under vacuum, and then brought to atmosphere to force the two together. The epoxy is allowed to cure in air for several hours at an elevated temperature. Once the epoxy is cured, then the mirror segment is separated from the mandrel. The segment is trimmed to its final shape for installation into its housing; the mandrel is cleaned in preparation for another replication cycle.

A number of factors contribute to the success of this approach. Inexpensive, durable mandrel material needed to be found. Drawn cylindrical borosilicate glass tubing manufactured by Schott has a surface with very low microroughness that is transferred to the epoxy. Mandrels are selected by scanning the surface of a tube to find portions with minimal curvature (typically less than 1 arcmin). The smooth microsurface of the mandrels allows the deposited reflective layer to release easily, with no need for a release layer. Additionally, since the reflective layer is deposited onto the mandrel, it is possible to use sputtering instead of evaporation. Sputtering yields a layer with density closer to bulk than evaporation and thus a higher X-ray reflectivity (the gold on the ASCA and BBXRT mirrors had density ~85 percent of bulk). For the replication to be viable, it was essential to find an epoxy that could be thinned to allow uniform spraying of a thin layer. A spraying process then needed to be developed that yields a uniform coating (this was done via robotic spraying – see Figure 7). Using a sufficiently thin epoxy layer minimizes transfer of large-scale mandrel surface features onto the substrate, meaning that the substrates retain the shape imparted to them through heat forming. The thin epoxy layer is also necessary to minimize distortions due to stresses built up during curing, as well as bilayer thermal deformation. Finally an epoxy cure cycle was developed that was not too cool, lest the epoxy cure insufficiently, nor too hot, lest the epoxy intermix with the reflecting material and spoil the surface quality.

Epoxy-replicated flight mirrors: Astro-E and Suzaku (Astro-E2)

Epoxy replication has become the baseline approach for making foil mirrors. The first epoxy-replicated mirrors were built for the Japan/US Astro-E mission. Included in the Astro-E instrumentation were five 40 cm diameter epoxy-replicated foil mirrors [14]. Four mirrors illuminated CCD detectors, which together comprise the XIS instrument. These mirrors had a focal length of 4.75 m, and consisted of 175 nested shells. The fifth mirror illuminated an X-ray microcalorimeter: a unique, nondispersive imaging spectrometer with high spectral resolution, that operates at a temperature of 0.065 K. This mirror had a 4.5 m focal length and consisted of 168 shells. The reflection stages of both mirror types again had an axial length of 10 cm. Each mirror had a mass of approximately 19 kg; the reflectors comprised over half the total mass.

area was essentially identical to that of the Astro-E mirrors. The same 20 percent reduction in effective area below the design area as for the Astro-E mirrors was found. It was shown that the loss of effective area due to misalignment between the mirror and the stray light baffle was at most 2 percent. A finished flight mirror is shown in Figure 8.

Figure 8: An Astro-E2 flight mirror, with stray light baffle attached on top. The aperture diameter is 40 cm; the height is approximately 22 cm. The mirror consists of 168 nested shells and has a mass of 20 kg. Between Astro-E and Astro-E2 (Suzaku) a total of 10 such mirrors were constructed.

Astro-E2 was successfully launched on July 10, 2005, and renamed Suzaku upon reaching orbit. Because of the loss of cryogen from the microcalorimeter cryostat prior to the start of observations, only the mirrors illuminating the CCD detectors were calibrated in orbit. The in-flight effective area was found to be consistent with ground calibration. A slight degradation of the angular resolution was noted immediately after launch: the on-orbit HPD of the four mirrors is 1.8-2.3 arcmin. The reduction is thought to be the consequence of mechanical relaxation of the foil segments in their housings stimulated by launch vibrations (the segments are not bonded in place). Over the nearly five years since launch there has been no detectable change in the performance of the mirrors.

Future Foil Mirrors: The Astro-H Soft X-ray Telescope, GEMS, and Astrosat

Astro-H is the next major Japan/US X-ray observatory, currently under development in Japan for a 2014 launch. Its instrumentation includes four X-ray mirrors: two Soft X-ray

(iv.) A modified alignment and mounting scheme will be used, incorporating two distinct sets of radial bars. One set of reference bars, with precisely located and shaped grooves, will be used as in the past to perform gang alignment of the mirror segments. A second set of support bars, with larger grooves will be interspersed with the reference bars, and the aligned segments will be bonded to them. After bonding, the accurate reference bars will be removed; only the second set will fly. Experiments using this approach on groups of 40-80 segments indicate improvement of the HPD to ≤1.2 arcmin.

(v.) The mirror has a substantially higher mass allowance (44 kg, compared with the 20 kg per Suzaku mirror). While the total mass of the mirror substrates is considerably larger than Suzaku (due to both the larger number of substrates and the use of thicker aluminum), the housing will comprise a larger fraction of the mirror mass (41 percent, compared with 25 percent for Suzaku). The resulting stiffer housing will reduce blur.
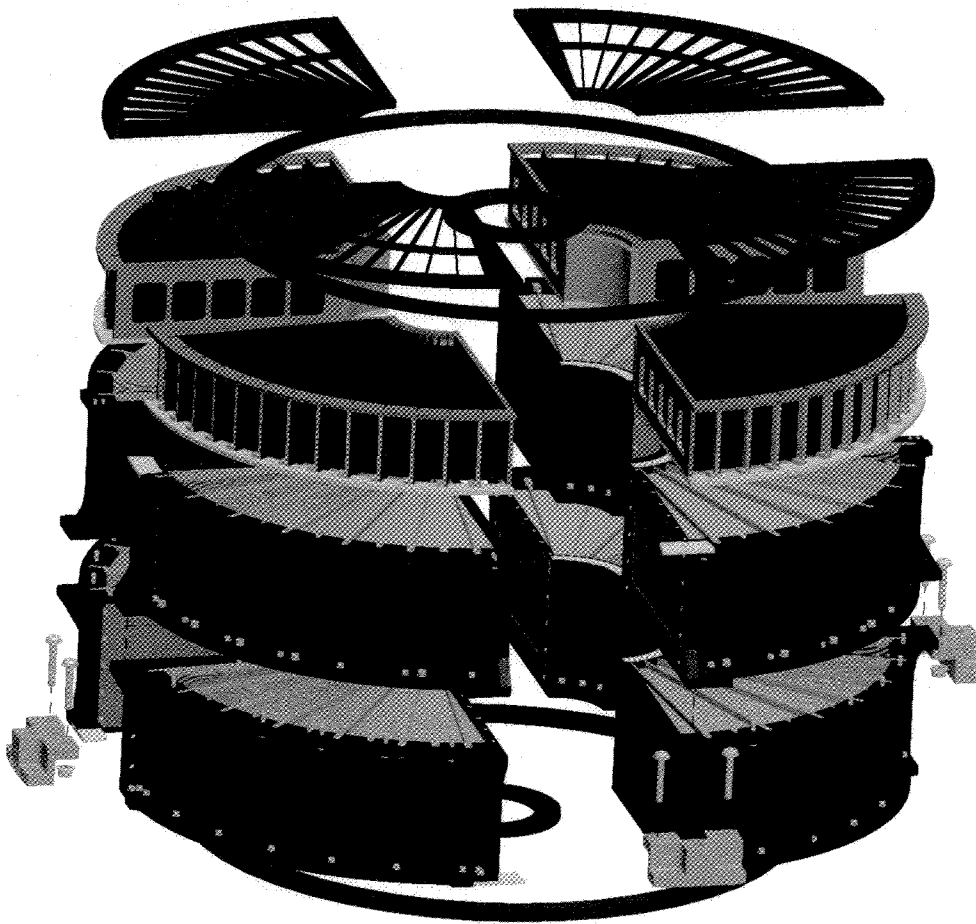

Figure 9: Exploded view of the Astro-H Soft X-ray Telescope. The mirror is segmented into quadrants. The main components, from the bottom, are: inner and outer lower mounting rings, the two reflection stages, the stray light baffle, the inner and outer upper mounting rings and the thermal shield. The overall dimensions of the assembled mirror are 47 cm in diameter and 25 cm high.

end of the band of interest, while the higher energy X-rays that penetrate more deeply into the layer are reflected by the deeper, more closely spaced layers. The original concept for graded multilayers introduced a power law layer variation with distance. Yamashita et al. [23] introduced the "supermirror" concept wherein the continuous gradation is replaced by a series of groups of identical thickness layers. They showed that the X-ray reflectivity of such a multilayer is comparable to that expected from an optimum grading.

Foil mirrors are attractive as high-energy mirrors because of their large geometric filling factor. With multilayers applied to the surfaces, they become efficient mirrors above 10 keV. Table 3 lists segmented multilayer mirrors that have either flown or are under construction.

Table 3: Multilayer coated foil mirrors

	InFOCμS	HEFT	SUMIT	NuSTAR
Diameter (cm)	40	24	36	38
Focal Length (m)	8	6	8	10
Number of Shells	255	72	90	130
Number of Modules per Mirror	4	1*	3	1
Segment Length (cm)	10	2x10**	13	22.5
Total Number of Segments	2040	700	540	2340
Substrate Material	aluminum	glass	aluminum	glass
Substrate Thickness (mm)	0.17	0.3	0.22	0.21
Surface Production Method	replication	thermal forming	replication	thermal forming
Multilayer Coating	Pt/C	W/Si	Pt/C	Pt/C, W/Si
Effective Area (cm^2)	51	50@40		150
Angular Resolution (arcmin)	2.7	1.3	2.06	<60
Year of Launch	2001, 2004	2005	2006	2012

The initial means for applying multilayers onto substrates was to coat the multilayers on top of the gold surface of an epoxy replicated segment [23]. This is an inherently slow and low yield approach because of the great care that must be taken to not damage the epoxy surface by overheating during deposition (The epoxy surfaces will be damaged if heated about ~40° C). It was subsequently demonstrated that multilayers could be replicated the same way as a gold monolayer: the multilayer is grown on a glass mandrel, and then transferred to the aluminum substrate using epoxy replication. This introduced a major advance in production speed and yield.

This approach was used to produce the first multilayer imaging mirror for hard X-rays [24, 25]. This mirror was used on the International Focusing Optics for MicroCrab Sensitivity (InFOCμS) balloon instrument, flown for the first time in 2001 (and an upgraded version flown twice subsequently), and has produced the first images of cosmic sources in the 20-40 keV band using multilayers. This mirror used the same fabrication, mounting and alignment techniques as used for Astro-E/E2, the only difference being the use of replicated multilayers for the reflecting surface instead of a gold monolayer. Like the Astro-E mirrors, it has a diameter of 40 cm, but it has a focal length of 8 m. A total of 255 nested shells are required. A graded Pt/C multilayer was transferred via epoxy replication onto each substrate. In the most recent mirror upgrade, the substrates were divided into 12 groups by radius, with the same multilayer prescription applied to each substrate in a group [26]. The block prescription introduced by Yamashita et al. [23] was

A number of error budget analyses for various foil mirror implementations have been presented (e.g., [30], [32]). The key contributors to blur include misalignment of segments within the housing, misalignment of primary and secondary segments, macroscopic axial figure errors on the foil surfaces, and distortions introduced by the mismatch between the segment shape and its location in the housing (effectively delta-delta-R errors). The intrinsic angular resolution due to the conical approximation is generally small compared with any of these terms. These analyses universally conclude that several terms contribute approximately equally. Thus all must be addressed if significant improvement is to be achieved. From the discussion above about the Astro-H SXT design, it can been seen both that incremental improvements are still being made and, more importantly, that addressing errors across a broad front can potentially lead to a considerably better mirror. Still it is unlikely that an aluminum foil mirror will ever achieve angular resolution substantially better than one arc minute. As we describe below, however, use of a different substrate material allows for construction of a high angular resolution mirror that preserves many of the desirable attributes of the foil mirror.

Glass as a substrate

Aluminum has numerous desirable attributes as a substrate material for foil mirrors: low density, easy to form, moderate cost, good surface properties. Nevertheless it is not ideal; it is flimsy, cannot be formed in three dimensions (i.e., cannot impart the axial curvature of a true Wolter mirror), and most importantly the surface quality of even the best material limits the attainable resolution to about an arc minute, considerably worse than the intrinsic resolution of the conical approximation for typical designs. Hailey et al. [33] performed a careful characterization of the surface properties of Al, and concluded that the surface properties limit the angular resolution of even a perfectly aligned aluminum foil mirror to 25 arcsec. Hailey was especially interested in a substrate to which multilayers could be applied. For a W/Si multilayer, Mao et al. [34] found that the interfacial roughness on glass (3.5—4.0 Å) was lower than that on an epoxy replicated foil (4.5—5.0 Å) (they did not try multilayer replication).

A number of alternative materials have been proposed: different metallic foil, silicon, carbon fiber reinforced plastic. Each of these materials introduces a new set of challenges. The most promising alternative material, and one that has produced a revolution in thin substrate mirrors, is glass. In searching for an alternative substrate for aluminum for hard X-ray mirror for a balloon instrument, Hailey et al. [33] showed that the intrinsic surface quality of commercially available borosilicate glass is far superior to that of aluminum. Moreover, the glass he investigated, commercially available Schott Desag D263 and AF45, has good mechanical properties, even at thicknesses of 200-400 μm. Hailey developed a thermal slumping approach to form the glass to its approximate shape. Multilayers could be directly deposited onto the glass substrate without a microroughness increase.

The slumping approach introduced by Hailey et al. [33] entails suspending a flat piece of glass substrate across a concave mandrel, and slowly thermally cycling it so that the glass
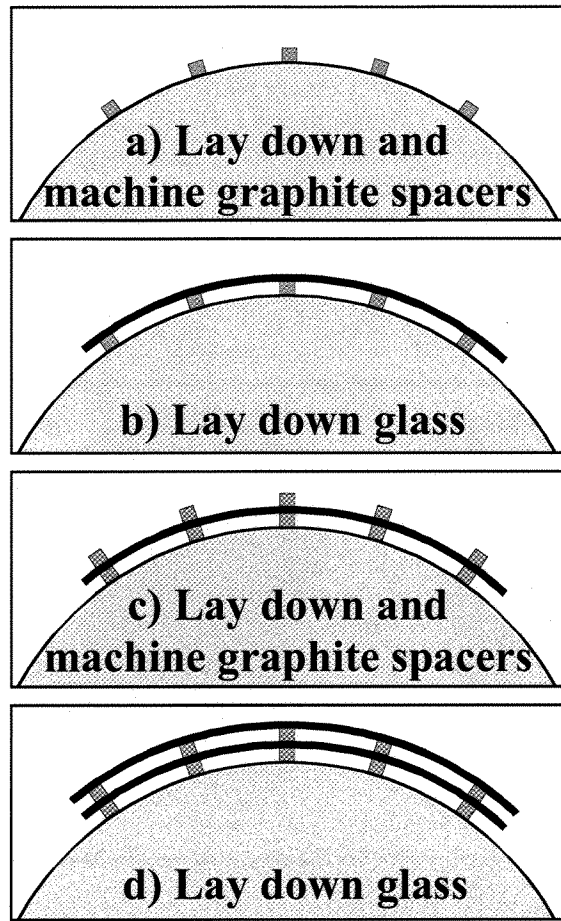
Figure 11: The mounting scheme for thermally formed glass mirrors invented for HEFT.
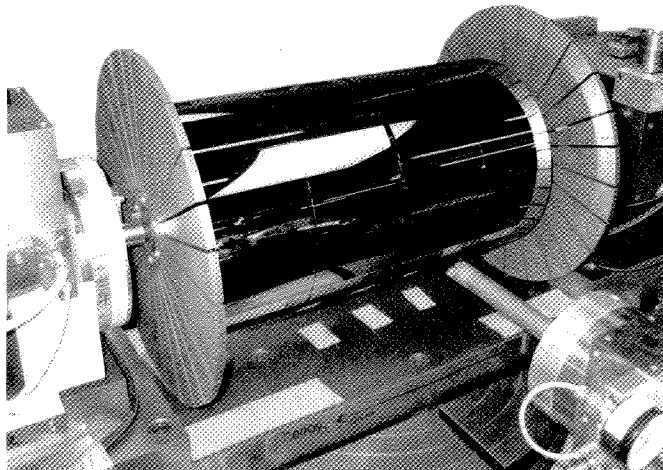

Figure 12: Fixture used to align and mount HEFT.

The mirrors are mounted and aligned using the approach developed for HEFT. Improved alignment machines have been fabricated.

Slumped glass mirrors for Constellation-X/XEUS/IXO

The introduction of slumped glass substrates stimulated work by a number of investigators seeking a means of forming thin substrates capable of providing high angular resolution. The motivation for this work comes from the consensus need for the next major X-ray astronomy mission – a substantial increase in collecting area combined with high angular resolution, to facilitate spatially resolved spectroscopy of distant (and hence faint) objects. The high angular resolution is driven by the need to perform spatially resolved spectroscopy of extended objects (clusters of galaxies, supernova remnants) as well as measure the spectrum of extremely faint objects without source confusion. The original NASA implementation was Constellation-X; the ESA implementation was the X-ray Evolving Universe Spectroscopy (XEUS). In 2007, these missions were merged into the International X-ray Observatory (IXO). For Constellation-X, the baseline implementation utilized slumped glass, with technology development led by GSFC. For XEUS, the baseline mirror was a Silicon Pore Optic (SPO). Slumped glass was considered a backup technology for XEUS, with technology development at the Max Planck Institut für Extraterrestrische Physik (MPE) and at the Osservatorio Astronomico di Brera (OAB). All three institutions are participating in the glass technology development for IXO.

The fundamental difference between Constellation-X and XEUS on one hand, and IXO on the other, are the size and performance specifications of the mirror. Constellation-X incorporated an array of four identical mirrors, each with a 1.3 m diameter and a 10 m focal length. The angular resolution was to be 15 arcsec HPD, with a goal of 5 arcsec. XEUS was to have a single mirror, with 5 m² of collecting area and a 50 m focal length. The angular resolution was to be 5 arcsec HPD, with a goal of 2 arcsec. IXO incorporates a single, large diameter mirror with 20 m focal length, 3.3 m diameter, and mass of 1750 kg. The effective area at 1.25 keV is to be at least 2.5 m² with a 3.0 m² goal, and 0.6 m² at 6 keV. The angular resolution of the entire observatory is to be 5 arcsec; to achieve this, the mirror angular resolution must be ~3-4 arcsec. Two approaches to the mirror are being pursued. ESA is developing a mirror based on silicon pore optics (SPO), wherein commercially available 0.773 mm thick Si wafers are stacked to form a conical approximation of a Wolter I mirror [38, 39, 40]. Careful stacking and alignment of the wafers leads to a mirror in which the dominant component of the angular resolution error budget is the conical approximation. The second approach, under study by NASA and independently in Europe at MPE and OAB, uses segmented glass substrates, slumped into a Wolter shape and mounted accurately into groups of identical modules [41, 42, 43]. Note that unlike previous implementations in which a conical approximation sufficed, true Wolter surfaces are required if the angular resolution requirement is to be met for IXO. But as for previous foil mirrors, a key design parameter in the IXO design is the effective area per unit mass.

corresponds to a blur of 8 arcsec. Mandrels and formed substrates are shown in Figure 15.

Use of a convex mold means that the X-ray reflecting surface comes into contact with the mandrel. The Columbia group used concave mandrels to avoid this contact, to ensure preservation of the excellent microroughness of the raw material. Zhang et al. have found that use of a suitable release layer on a convex mold preserves the microsurface quality [41]. The microroughness degradation is measured to be a most 1 Å. The challenges faced in forming precise mirror segments are threefold: (i.) Mandrels with sufficiently high quality figure need to be mass produced. (ii.) Distortions introduced into the glass from the slumping must be controlled. The most destructive distortions are those with spatial frequencies in the millimeter to centimeter range, the so-called mid-frequency errors. (iii.) Any X-ray reflective coating deposited onto the substrate must not distort it via bimorphic stresses.
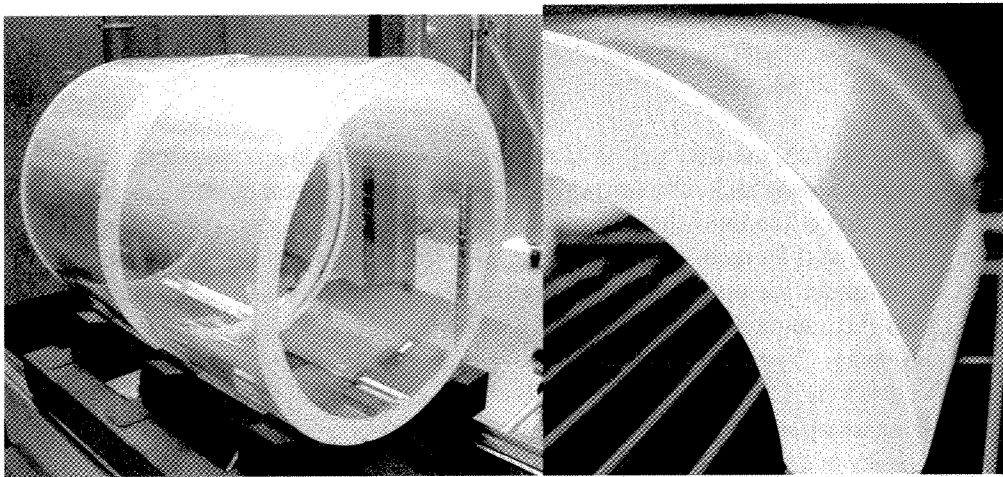

Figure 15: Two views of thermally formed glass substrates for IXO on mandrels. The mandrels are fused silica; each is approximately 50 cm in diameter. The two mandrels shown represent the primary and secondary reflection stages for a particular shell.

Of the three challenges, the most formidable is the control of the mid-frequency errors. Several optics manufacturers have the capability for producing mandrels of the required quality and quantity. Experiments have demonstrated that the bimorphic stresses imparted by iridium, the reflective coating of choice, can be compensated by the use of an undercoating material (such as chromium) that imparts opposite stress,. Control of the mid-frequency errors depends on the release layer surface quality. Current experiments are concentrated on a boron nitride coating. Once the coating is applied, it must be conditioned through a series of buffing and thermal cycling steps.

Results to date are promising. It has been shown that the formed substrates conform to the mandrel figure with very high fidelity. For a number of reasons, the required figure

at MPE [42]. Although mandrel fabrication for this approach is more challenging, the complexity of aligning the primary and secondary surfaces is avoided, and alignment errors thereby reduced.
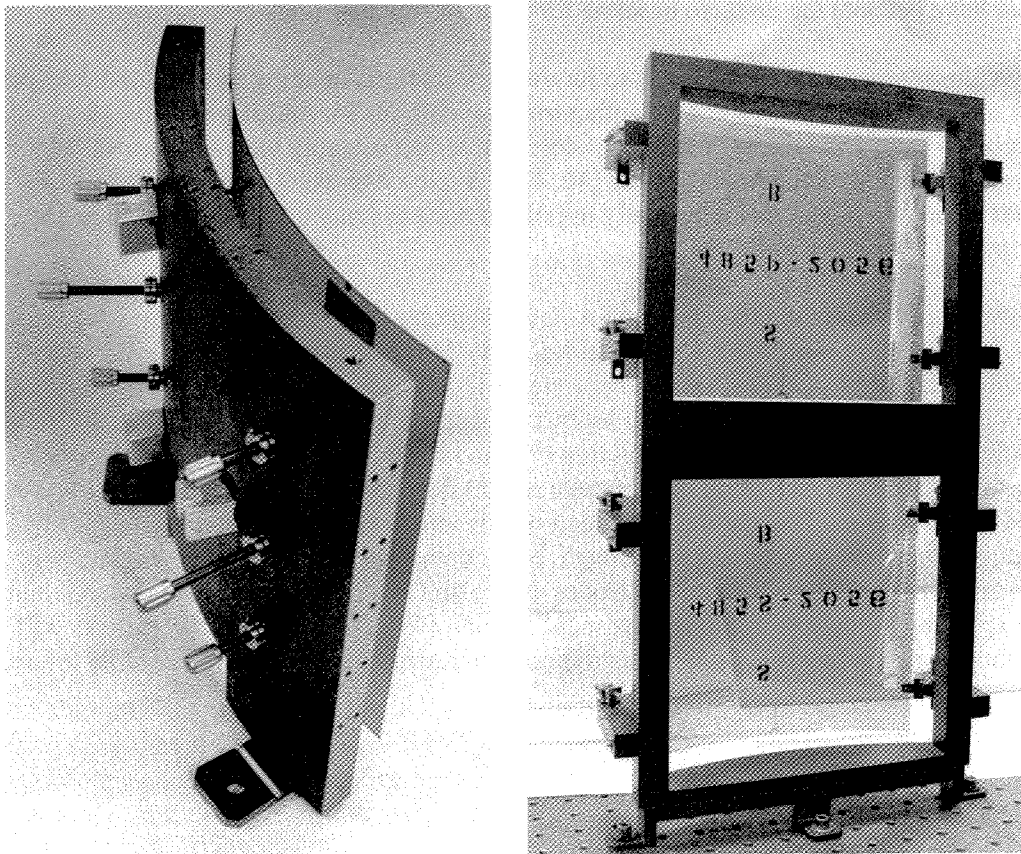

Figure 16: (left) Rear view of an IXO mirror on a strongback for transfer to a permanent mount. The six actuators provide the mounting points. (right) A pair of uncoated IXO mirror segments mounted in a prototype permanent mount.

The future of segmented mirrors

The evolution of thin, segmented X-ray mirrors since their introduction 30 years ago has been remarkable. No longer are they merely considered as concentrators for enhancement of focal instrument sensitivity (although they still play that role on, e.g., GEMS). Through the introduction of new surface deposition methods (multilayers) and substrates (glass), they have evolved into the mirror of choice for high energy imaging (NuSTAR, the Astro-H HXT, and the hard X-ray capability on IXO). With the introduction of accurate substrate forming and precision mounting, they also now have the potential to provide high angular resolution. At the same time, their key advantages –

References

1. Serlemitsos, P. J., "The Broad-Band X-Ray Telescope," 1981, in X-ray Astronomy in the 1980's, ed. S. S. Holt, in NASA TM 83848

2. Serlemitsos, P. J., "Conical foil x-ray mirrors: performance and projections," 1988, Appl. Opt. 27, 1447

3. Petre, R., & Serlemitsos, P. J., "Conical imaging mirrors for high-speed x-ray telescopes," 1985, Appl. Opt. 24, 1833

4. Figueroa-Feliciano, E., et al., "Progress on the Micro-X rocket payload," 2008, Proc. SPIE, 7011, 70113U

5. Weaver, K. A., et al. "Calibrating the Broad Band X-Ray Telescope," 1995, ApJS, 96, 303

6. Tanaka, Y., Inoue, H., & Holt, S. S., "The X-ray Astronomy Satellite ASCA," 1994, PASJ, 46, L37

7. Serlemitsos, P. J., et al. "The X-ray Telescope on board ASCA," 1995, PASJ, 47, 105

8. Schnopper, H. W., "SODART telescopes on Spectrum X-Gamma (SRG) and their complement of instruments, 1994, Proc. SPIE, 2279, 412

9. Polny, J., Westergaard, N. J., Christensen, F. E., Nielsen, H. U. N., & Schnopper, H. W., "Production, assembly and alignment of the XSPECT Mirror Modules for the SODART X-ray telescope on the Spectrum Röntgen Gamma satellite," 1997, Proc. SPIE, 3113, 349

10. Christensen, F. E., Madsen, B., Hornstrup, A., Abdali, S., Frederiksen, P., Westergaard, N. J., Polny, J., Budtz-Jorgensen, C., Jonasson, P., Hall, C. J., & Lewis, R. A., 1997, "X-ray calibration of the SODART flight telescopes," Proc. SPIE, 3113, 294

11. Serlemitsos, P. J., & Soong, Y., "Foil X-ray Mirrors," 1996, Ap. Sp. Sci., 239, 177

12. Laine, R., Giralt, R., Zobl, R., de Korte, P. A. J., & Bleeker, J. A. M., "X-ray imaging telescope on EXOSAT," 1979, Proc. SPIE, 184, 181

13. Rasmussen, A., Cottam, J., Decker, T. A., Kahn, S. M., Spodek, J., Stern, M. Erd, C., den Boggende, A. J., Brinkman, A. C., den Herder, J.-W., Paerels, F. B., & Vries, C. D., "Performance characterization of the reflection grating arrays (RGA) for the RGS experiment aboard XMM," 1998, Proc. SPIE 3444, 327

14. Kunieda, H., et al., "X-ray telescope onboard Astro-E: optical design and fabrication of thin foil mirrors," 2001, Appl. Opt., 40, 553

30. Ogasaka, Y., et al., "Thin-foil multilayer-supermirror hard X-ray telescope for InFOCμS / SUMIT balloon experiments and the NeXT satellite program," 2007, Proc. SPIE, 6688, 668803

31. Awaki, H., et al. "Current status of the Astro-H X-ray Telescope system," 2009, Proc. SPIE, 7347, 734703-1

32. Kunieda, H., & Serlemitsos, P. J., "X-ray mirror assessment with optical light," 1988, Appl. Opt., 27, 1544

33. Hailey, C. J., Abdali, S., Christensen, F. E., Craig, W. W., Decker, T. R., Harrison, F. A., & Jimenez-Garate, M. A., "Investigation of substrates and mounting techniques for the High Energy Focusing Telescope (HEFT)," 1997, Proc. SPIE, 3114, 535

34. Mao, P. H., Harrison, F. A., Platonov, Y. Y., Broadway, D., Degroot, B., Christensen, F. E., Craig, W. W., & Hailey, C. J., "Development of grazing incidence multilayer mirrors for hard x-ray focusing telescopes," 1997, Proc. SPIE, 3114, 526

35. Koglin, J., et al., "Hard X-ray Optics: from HEFT to NuSTAR," 2004, Proc. SPIE, 5488, 856

36. Koglin, J., et al., "Calibration of HEFT Hard X-Ray Optics," 2006, in "X-ray Universe 2005," ed. A. Wilson (ESA SP-604) p. 955

37. Koglin, J., et al., "NuSTAR Hard X-ray Optics Design and Performance," 2009, Proc. SPIe, 7437, 74370C-1

38. Bavdaz, M., et al., "IXO system studies and technology preparation," 2009, Proc. SPIE, 7427, 743702-1

39. Collon, M., et al., "Stacking of Silicon Pore Optics for IXO," 2009, Proc. SPIE, 7347, 74371A-1

40. Bavdaz, M., Collon, M., Beijersbergen, M., Wallace, K., & Wille, E., "X-ray Pore Optics Technologies and their Application in Space Telescopes," 2010, X-ray Optics and Instrumentation, v. 2010, Article ID 295095

41. Zhang, W. W., et al. "Mirror technology development for the International X-ray Observatory mission," 2009, Proc. SPIE, 7437, 74370Q-1

42. Vongehr, M., Friedrich, P., Bräuninger, H., Lieb, W., Fürmetz, M., Mazur, A., Veit, K., Ettl, P., & Laboureux, X., "Experimental results on slumped glass x-ray mirror segments," 2007, Proc. SPIE, 6688, 66881A-1