# Next Generation X-ray Optics:
High-resolution, Light-weight, and Low-cost

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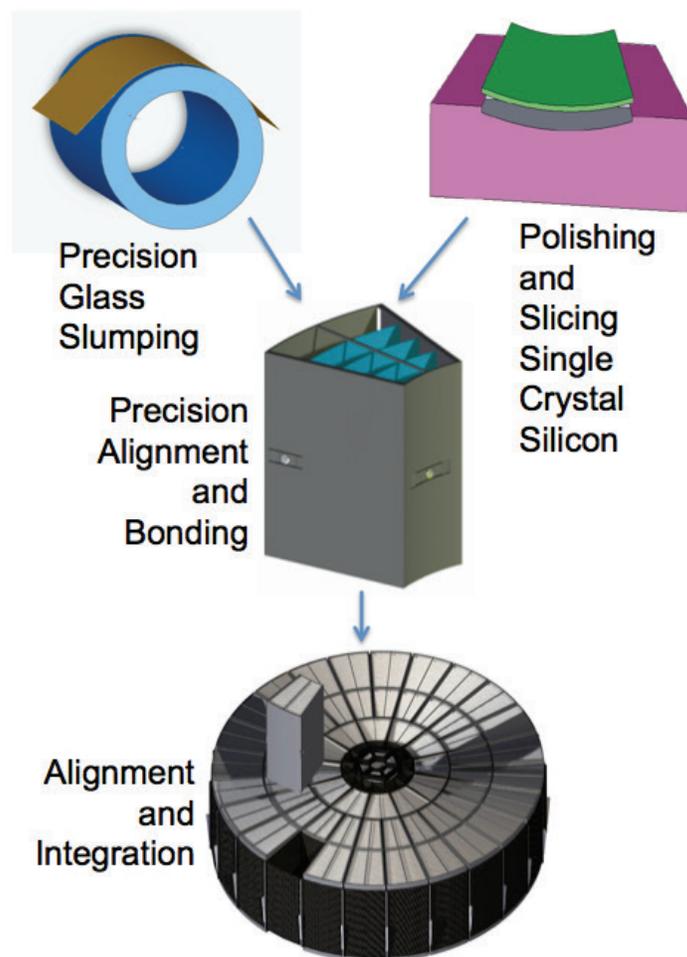
Summary

X-ray telescopes are essential to the future of x-ray astronomy. This paper describes a comprehensive program to advance the technology for x-ray telescopes well beyond the state of the art represented by the three currently operating missions: *Chandra*, XMM-*Newton*, and *Suzaku*. This program will address the three key issues in making an x-ray telescope: (1) ***angular resolution***, (2) ***effective area per unit mass,*** and (3) ***cost per unit effective area.*** The objectives of this technology program are (1) in the near term, to enable Explorer-class x-ray missions and an IXO-type mission, and (2) in the long term, to enable a flagship x-ray mission with ***sub-arcsecond*** angular resolution and ***multi-square-meter*** effective area, at an ***affordable*** cost. We pursue two approaches concurrently, emphasizing the first approach in the near term (2–5 years) and the second in the long term (4–10 years).

The first approach is ***precision slumping*** of borosilicate glass sheets. By design and choice at the outset, this technique makes lightweight and low-cost mirrors. The development program will continue to improve angular resolution, to enable the production of 5-arcsecond x-ray telescopes, to support Explorer-class missions and one or more missions to supersede the original IXO mission.

The second approach is ***precision polishing and light-weighting of single-crystal silicon mirrors***. This approach benefits from two recent commercial developments: (1) the inexpensive and abundant availability of large blocks of monocrystalline silicon, and (2) revolutionary advances in deterministic, precision polishing of mirrors. By design and choice at the outset, this technique is capable of producing lightweight mirrors with sub-arcsecond angular resolution. The development program will increase the efficiency and reduce the cost of the polishing and the light-weighting processes, to enable the production of lightweight sub-arcsecond x-ray telescopes.

Concurrent with the fabrication of lightweight mirror segments is the continued development and perfection of alignment and integration techniques, for incorporating individual mirror segments into a precision mirror assembly. Recently, we have been developing a technique called ***edge-bonding***, which has achieved an accuracy to enable 10-arcsecond x-ray telescopes. Currently, we are investigating and improving the long-term alignment stability of so-bonded mirrors. Next, we shall refine this process to enable 5-arsecond x-ray telescopes. This technology development program includes all elements to demonstrate progress toward TRL-6: metrology; x-ray performance tests; coupled structural, thermal, and optical performance analysis, and environmental testing.

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1. Introduction

The importance of x-ray optics was duly recognized as soon as celestial x-ray sources were discovered (Giacconi & Rossi 1960). In a sense, the past 50 years of x-ray astronomy represent a continual push of the envelope of optics manufacturing technology to satisfy the observational priority at any given time. The three currently operating missions,—*Chandra*, XMM-*Newton*, and *Suzaku*—are culminations of those efforts.

Each of those x-ray telescope systems is a scientifically useful compromise amongst three parameters: ***angular resolution***, ***effective area per unit mass***, and ***cost***. *Chandra* (Gordon & Catching 1994) achieves an exquisite angular resolution (0.5-arcsecond half-power diameter, HPD), but a relatively small effective area (800 cm^2 at 1 keV, for 1,500 kg mass), at a very high cost ($600M in 1995). *Suzaku* (Serlemitsos et al. 2007) achieved a large effective area (400 cm^2 at 1 keV, per telescope), for very little mass (16 kg per telescope), at a very low cost ($1M per telescope), but with poor angular resolution (120-arcsecond HPD). XMM-*Newton* (Gondoin et al. 1994), with moderate angular resolution (15-arcsecond HPD) and large effective area (1,500 cm^2 at 1 keV, for 420 kg mass), falls between *Chandra* and *Suzaku* in this parameter space.

Three parameters characterize an x-ray optics technology: (1) angular resolution, (2) effective area per unit mass, and (3) cost per unit effective area. In terms of the first two parameters, Figure 1 shows that the three current missions form a boundary separating the past and future of x-ray telescopes. The upper left embodies the past: Telescopes are relatively easy to build but less powerful. The lower right embodies the future: Telescopes are more powerful but challenging to build; thus they require significant technology development.
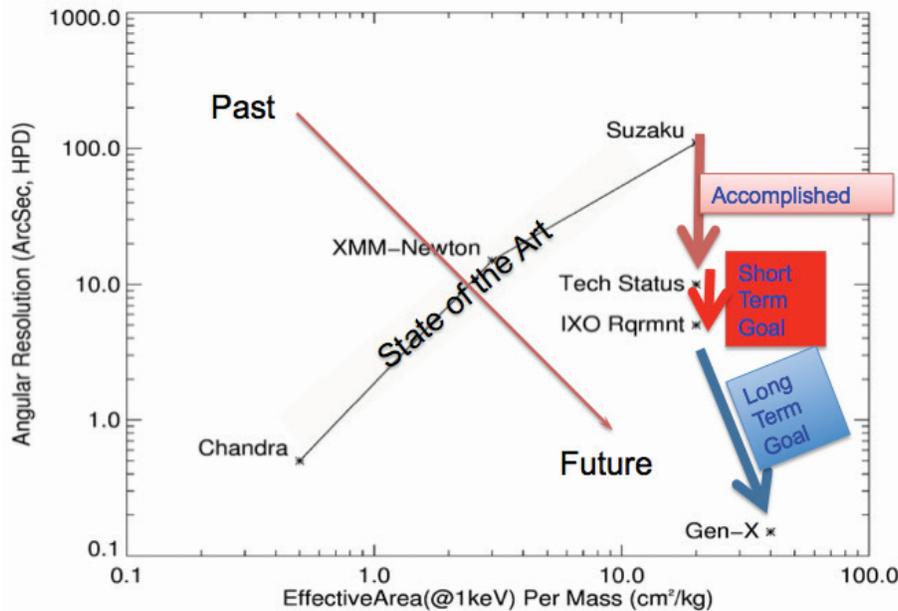

Figure 1.—Angular resolution and effective area per unit mass of the three currently operating x-ray telescopes. This technology program starts with *Suzaku*'s effective area per unit mass and strives to improve its angular resolution. The short-term goal is to achieve 5-arcsecond HPD (half-power diameter) required by the IXO mission concept; the long-term goal is to meet the requirements of the *Generation-X* advanced concept (Zhang et al. 2001; Windhorst et al. 2006).

IXO's science goals and mission implementation were well received by the Astro-2010 Decadal Survey. However, IXO's ranking as fourth priority makes it infeasible to begin development before 2020, owing mainly to its perceived technical risk and high cost. The perceived risk results primarily from the absence of a demonstrated technology for cost-effective manufacturing the x-ray telescope. The IXO telescope would have had an outer diameter of 3 meters, an effective area of 3 m^2 at 1 keV, and an angular resolution of 5 arcseconds. As our community regroups to prepare for one or more missions that can accomplish IXO's major science goals at a much lower (<<$5B) cost, we recognize that any replacement mission will need x-ray optics that provide similar or better angular resolution (5 arcseconds), at a credibly and significantly lower cost. Table 1 lists several mission concepts that could accomplish some or all the scientific objectives of IXO.

Table 1.—Each of these example mission concepts could realize some of IXO's science goals at a much lower cost. A common feature of these concepts is the need for an x-ray telescope with good angular resolution and large effective area at a relatively low cost: These are exactly the goals of this technology-development program.

Mission Concepts	Major Science Goals	X-ray Telescope Requirements
De-scoped IXO with both gratings and calorimeters (AXSIO, Bookbinder et al. 2011)	Matter under extreme conditions; Neutron star equation of state; Black hole evolution; Large scale structure; Galaxy clusters; etc.	A mirror assembly similar to IXO's with a smaller diameter, but with ~10 arcsecond angular resolution
Soft X-ray spectroscopy with gratings (AEGIS, Bautz et al. 2011)	Inter-galactic and inter-stellar media; Astrophysical plasmas; Star-burst galaxies, Galaxy clusters; SNRs, etc.	A mirror assembly with an angular resolution of 10 arcseconds or better, but with several thousand cm^2 of effective area at 1 keV
Soft X-ray spectroscopy with calorimeters (SaHara, Mushotzky et al. 2011)	Clusters of galaxies; Star-burst galaxies; SNR; etc.	A mirror assembly with an angular resolution of 5 arcseconds or better, but with several thousand cm^2 of effective area at 1 keV
Hard X-ray telescopes (BEST, Krawczynski et al. 2011; HEP, Harrison et al. 2011)	Black hole spin; Cosmic hard x-ray background; AGNs, etc.	Multiple mirror assemblies, each of which is comparable to a NuSTAR mirror assembly but with ~10 arcsecond angular resolution

We adopt a two-pronged approach to develop the necessary technologies for making future x-ray telescopes. As the first prong, in order to fulfill the ***mandate of the Decadal Survey***, we continue the development of slumped-glass technology to ready it for a mission that is substantially similar to, but less expensive than, the original IXO. As of October 2011, this technology meets angular-resolution, mass, and cost and schedule requirements of building a 10-arcsecond telescope, such as AXSIO (Bookbinder et al. 2011). At issue is that the technology has not been rigorously engineered with the building and testing of prototypes to retire cost and schedule risks associated with implementing a new technology on a relatively large system scale. The thrust of this program is to refine and perfect the many techniques that have been developed in the last several years, build and test prototypes to demonstrate TRL-5 in the near term to enable a new mission—such as one of those identified in Table 1— to enter Phase A.

As the second prong, we recognize the obvious desire of astrophysicists for ***a telescope with an angular resolution comparable to or better than Chandra's but with at least one-order-of-magnitude increase in effective area***. Given anticipated budgetary constraints, this telescope has to be manufactured at a cost comparable to that of Chandra's telescope ($600M in 1995), or less. Since completion of the *Chandra* optics, two significant, relevant developments have occurred. In the semiconductor industry, large blocks of ***single-crystal silicon*** have become abundantly available at low prices. In the optics fabrication industry, several ***polishing techniques*** have been developed and commercialized to make deterministic, precision polishing routine. We shall adapt these two developments to the process of making lightweight x-ray mirrors, using a two-step process. First a thick silicon mirror is made by polishing to achieve the best angular resolution possible, ~0.1 arcseconds. In contrast with ordinary glass or glassy ceramics, monocrystalline silicon has no internal stress. Thus, the light-weighting process will not change the figure of the monocrystalline-silicon mirror. By design and implementation, this approach can potentially make lightweight mirrors with exquisite angular resolutions (~0.1 arcseconds). The thrust of our technology development program in this area is to ***increase the efficiency and reduce the cost*** of this process, such that it is affordable for a flagship x-ray mission in the 2020's.

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2. Technology Development Paradigm and Strategy

In the past, both full-shell designs and segmented designs have been used in building x-ray telescopes. It is generally accepted that all future large x-ray telescopes will use the segmented design, which is modular and scalable to very large collecting areas. Larger areas in general require *larger diameters and thinner mirrors*. These two factors—large diameter and thin mirrors—render large full-cylinder mirrors impractical to build and measure. In contrast, the scalability of segmented optics allows the construction of arbitrarily large x-ray telescopes by fabricating and integrating a large number of small modules, each of which is of a manageable size and relatively stiff.

Figure 2 illustrates the paradigm of the segmented design. The flight mirror assembly is segmented in both radial and azimuthal directions, into a number of wedge-like modules. All modules are substantially similar in dimensions and in the number of mirror segments they contain. The entire process of constructing the mirror assembly comprises three steps: (1) Fabricate the mirror segments necessary to populate the modules; (2) align and attach the mirror segments into modules; and (3) align and attach the modules into the telescope mirror assembly.

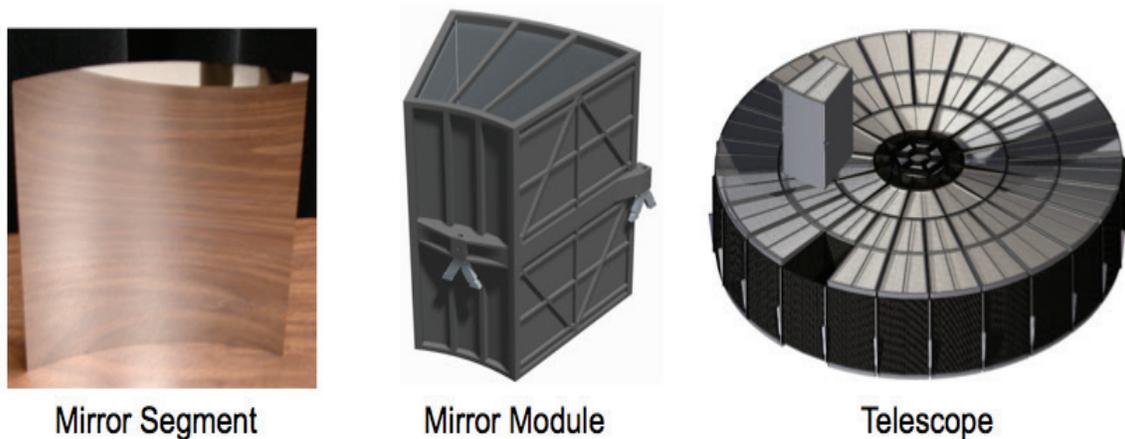Mirror Segment   Mirror Module   Telescope

Figure 2.—Hierarchical structure of a segmented design: mirror segment, mirror module, and telescope mirror assembly. Nominally, a mirror segment is 200 mm × 200 mm; a mirror module contains ≈100 co-aligned mirror pairs (primary and secondary); and a telescope mirror assembly comprises of order 100 aligned and integrated modules.

This segmented approach has several practical and important features. The small size of the mirror segments, typically measuring 200 mm by 200 mm (Biskach et al. 2011), allows them to be measured and manufactured using existing equipment and facilities. Thus, there is no need to spend an extraordinary amount of money to build unique facilities. This small size also allows the manufacture and testing of these mirror segments to be contracted to many vendors, stimulating competition and thereby lowering cost. Another important feature is that many modules are identical; thus mass production can significantly lower the cost and shorten the schedule of mission implementation.

We adopt a time-tested rigorous approach to the development process, which includes an allocation of the imaging error budget (Table 2) to the major steps in constructing the x-ray telescope (Figure 2). This strategy requires that each major step and sub-step meet strict quantitative criteria, without assuming that an un-budgeted error in a particular step can be corrected in a later step. This minimizes unintended consequences at the systems level. For example, we don't attempt to correct an un-budgeted error in the mirror segment, during integration of the mirror into the module. The rationale is that any correction of mirror figure during assembly will necessarily impart a force or moment into the module housing, which might distort the housing and ultimately the other mirror segments in the module. Instead our approach is that each mirror segment exerts no more load to the module housing than its own weight, which is known and whose effect is accurately predictable.

Table 2.—Imaging error allocation to, and high-level description of, the three major steps in constructing a segmented x-ray telescope. The four example angular-resolution requirements may entail very different methods for making mirror segments, as well as for aligning, testing, and qualifying mirror modules.

Major Step	Description	Near Term Objectives (2 to 4 years)		Long Term Objectives (4-10 years)	
		10-arcsec Obs.	5-arcsec Obs.	1-arcsec Obs.	0.1-arcsec Obs.
Mirror segments	Each mirror segment must be good enough in every aspect: focal length, figure, and micro-roughness. Each mirror segment must be individually and completely and independently measured and verified to meet all requirements, in particular the image performance requirement in the next four columns	< 7	< 3.5	< 0.7	< 0.07
Mirror Modules	Each mirror module is tested and verified to meet both performance and environmental requirements; With the segmented design, these modules are relatively small in size and can be tested with existing equipment or easily constructed facilities; the module construction process should not contribute more to the imaging error than the numbers in the next four columns	< 5	< 2.5	< 0.5	< 0.05
Flight Mirror Assembly	Each module must be accurately aligned and located to a superstructure. Mechanical, thermal, and other factors that can potentially degrade image quality must be quantified, including launch shifts, gravity release, detector pixel size; All these factors should not contribute more imaging error than the numbers in the next four columns	< 5	< 2.5	< 0.5	< 0.05
Technology and Implementation Note		(1) Mirror segments are fabricated by slumping ordinary glass sheets; (2) Construction and testing of modules can be done in an ordinary laboratory environment; (3) X-ray performance tests can be done with a horizontal x-ray beam line that currently exists in many places, although preferably in a vertical beam-line.		(1) Mirror segments must be made of single crystal silicon for its superior thermal and mechanical properties; (2) Module construction must be done in a highly regulated and controlled thermal environment; (3) X-ray performance test must be done with a vertical x-ray beam-line.	

3. Technology Development Process

With the strategy outlined above, this technology development program focuses on perfecting several important techniques, with proper attention to systems-level issues where warranted. This approach will fully develop the requisite technology and qualify it to TRL-5: "*A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases.*" (NASA NPR 7120.8 – Appendix J) A higher TRL will be achieved by demonstrating higher-fidelity mirror modules for specific telescope designs associated with a well-defined mission concept. It is usually fully achieved by the end of Phase-A or Phase-B.

3.1 Mirror Segment Fabrication

A mirror segment is a figured substrate coated with a reflectance-enhancing metallic film. The coating is typically an iridium layer (possibly with an overcoating) for a soft x-ray telescope, or multi-layers inter-leaving heavy and light elements for a hard x-ray telescope. The substrate must meet a number of requirements, including mass per unit surface area, dimensional accuracy for the installation into a module housing, precise geometric figure for minimal image blur, and low surface micro-roughness to eliminate unacceptable scattering of x rays.

3.1.1 Mirror Substrate Fabrication

We are developing two totally different methods of substrate fabrication: (1) precision glass slumping and (2) figuring and polishing and light-weighting of mono-crystalline silicon. The two methods differ in their approaches and in fundamental considerations.

3.1.1.1 Precision Slumping of Glass

The precision slumping of glass, as illustrated in Figure 3 is a replication technique. It results in lightweight and inexpensive mirrors starting with thin (0.4 mm or thinner) commercially available glass sheets. From the outset, it already meets two (*light weight* and *low cost*) of the three requirements. Consequently, the objective of the glass-slumping development is to improve the *angular resolution*.

Figure 3.—Left and middle: In the glass slumping process, a thin float-glass sheet slumps under its own weight as the temperature ramps gradually to ~ 600ºC, replicating the mandrel's precise figure. Right: Histogram of the figure quality of 32 pairs of consecutively produced mirrors gives a mean imaging quality is 6.5-arcsecond HPD (two reflections), satisfying the allocation for making a 10-arcsecond telescope.

As of October 2011, we have demonstrated fabrication of forming mandrels (Blake et al. 2011) and reliable slumping of substrates that meet the requirements of a 10-arcsecond telescope system (Zhang et al. 2011, Chan et al. 2011). Currently produced mirrors consistently exhibit an HPD (two-reflection) close to the 7-arcsecond allocation (Figure 3, right). In 2012 and 2013 we shall continue to improve the precision of the glass-slumping process toward reducing the substrate figure error by a factor of two, in order to meet the mirror allocation for a 5-arcsecond telescope system. Achieving this improvement requires several steps. The first is to reduce mid-frequency ripples caused by the roughness of the boron-nitride release layer. We have continually reduced this error by inventing new methods for coating and buffing the release layer. We expect that, with proper funding, we can reduce the roughness by another factor of two. The second step is to improve the cleanliness of the oven environment in which the slumping occurs: Dust particles sandwiched between the glass sheet and mandrel cause ripples that degrade the imaging performance. The third step is to improve the temperature uniformity within the oven: A necessary conditions for making good substrates is to keep the entire glass sheet in thermal equilibrium, as any temperature gradient across the glass sheet can cause permanent figure distortion during slumping and cooling.

3.1.1.2 Precision Polishing and Light-weighting of Monocrystalline Silicon

The second method of making mirror substrates, which has been devised and begun to be investigated only recently, benefits from two technological developments over the past two decades: (1) commercial availability of inexpensive large blocks of monocrystalline silicon, and (2) commercial availability precision optical polishing machines. The salient feature of monocrystalline silicon is that it is free of *internal stress* because each atom is in its proper position. In contrast, glass or other materials from which optics are usually made have large internal stresses. An important consequence of this difference in internal stress is that a thick silicon mirror can be light-weighted without losing its figure, provided that surface damage caused by the light-weighting process is properly removed, whereas a glass (or glass ceramic) mirror cannot. Figure 4 illustrates the process of making a lightweight silicon mirror. It starts with a block of monocrystalline silicon out of which a segmented parabolic or hyperbolic mirror is ground and polished with commercially available polishing machines (e.g., QED Technologies' Magneto-Rheological Finishing machines, or ZEEKO's specially designed and standardized polishing machines). Once this mirror is finished and qualified in every aspect, it is light-weighted by a slicing process that removes a thin face-sheet of the mirror. The slicing operation necessarily causes surface damage that will distort the now-thin mirror. However, subsequent

annealing and chemical etching removes the surface and subsurface damage, thus restoring the original figure of the mirror.

This method of making mirrors already meets two (***angular resolution*** and ***light weight***) of the three requirements. The objective of our technology development is to reduce cost to a level affordable for a spaceflight mission. In 2012 we plan to demonstrate the principle outlined above by making thin (0.4-mm) flat silicon mirrors. Once successful we shall make a few parabolic and hyperbolic mirrors to demonstrate that the principle also applies to making curved mirrors. In subsequent years, we shall seek to systematize a polishing and light-weighting process to minimize the cost of making a mirror segment. Preliminary estimates indicate that it is plausible for this process to make mirror substrates at a low enough cost to enable a mission like IXO, which would require 15,000 mirror substrates, each about 200 mm by 200 mm. Allowing $150M for making mirror substrates, we need to reduce the cost to less than $10,000 per mirror segment. According to industry experts, this is easily achievable with adequate investment in facilitization.
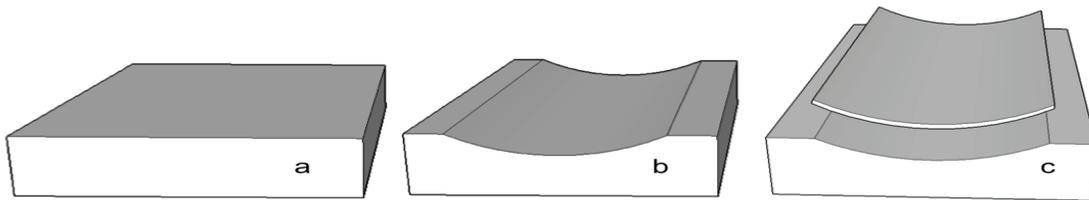

Figure 4.—Illustration of the three steps for making a high-resolution Wolter-I mirror substrate: (1) A block of monocrystalline silicon, properly cut and etched to remove all subsurface damage caused by the cutting; (2) a conical shape is directly cut (using a wire-EDM process or a diamond-studded wire-saw) and precision figured and polished after removing subsurface damage with a chemical etch; and (3) the mirror is sliced off the silicon block and the back (convex) surface is etched to remove subsurface damage. The resulting mirror substrate is expected to have the same figure as before slicing because the mirror substrate is still a single crystal free of any stress.

Mirror figure quality improvement and cost reduction go hand-in-hand. We shall start by making 2-arcsecond mirror substrates that can be easily achieved, both in terms of metrology accuracy and material removal accuracy. There are two significant advantages that segmented x-ray optics afford the fabrication process: near cylindrical geometry, and total access due to the fact that each mirror is almost flat. One important point is that silicon is probably the best understood material because of the semiconductor industry. Very efficient polishing and super-polishing processes have been developed and perfected. The easy and inexpensive availability of super-polished silicon wafers is a testament to this fact. Making mirror substrates this way allows us to tap into an extensive knowledge base that has been accumulated over the past 50 years.

3.1.2 Coating

Substrates need to be coated with a thin metallic film to optimize x-ray reflectance and thus the effective area of an x-ray telescope. Depending upon the x-ray energy band of interest, one uses either a single layer of iridium coating (potentially with an overcoat) for soft x-rays (0.1–10 keV) or a stack of multi-layers of interleaved high-Z and low-Z materials for hard x rays (6–100 keV). In either case, thin films can create significant stress, degrading the optical figure of a thin substrate. We are actively investigating two coating methods to mitigate coating stress: magnetron sputter and atomic layer deposition (ALD).

3.1.2.1 Magnetron Sputter

Magnetron sputter has been used many times to coat x-ray mirrors. Its advantages include achieving close to bulk density, very low micro-roughness, and high rates of deposition. Its main disadvantage is that the film stress can be high, resulting in severely distorted mirror segments. We are investigating two methods for reducing this distortion. In the first method, we take advantage of the fact that sputtered iridium film tends to have compressive stress whereas sputtered chromium film, tensile stress. A bi-layer coating of first a chromium film and then an iridium film, with proper thicknesses, can result in near-zero net stress on the mirror substrate. Using small coupons, Dr. David Windt of Reflective X-ray Optics LLC has demonstrated the stresses of the two films can indeed cancel each other. We are working with Dr. Windt to apply this recipe to coating full-size mirror substrates. The second method we are investigating is to coat simultaneously both the concave and convex sides with an equal thickness of iridium, such that the stresses on the opposite surfaces balance.

3.1.2.2 Atomic Layer Deposition

Atomic Layer Deposition (ALD) has become increasingly a practical means of coating optics. Its advantage is manifold. First, it is totally conformal, coating every surface exactly the same way with exactly the same thickness. Second, its heating of the substrate under coating is more uniform and benign, in contrast to the ballistic heating caused by sputter. Third, it is believed not to degrade the micro-roughness of the substrate as more atomic layers are coated. Fourth, it can be an efficient and fast process. Each atomic layer can be deposited in a matter of seconds, determined by how fast residual gas can be pumped from the chamber. The most important feature that serves our current purpose is its conformal feature. Even if ALD can cause local stress, the fact the front and back of the mirror substrate are coated simultaneously and with the same thickness would ensure that the final mirror segment is distortion-free. We are conducting experimentation with small coupons to investigate the feasibility and parameters of coating iridium on Schott D263 glass in collaboration with a group at University of Maryland-College Park. If successful, we will proceed to coat full-size Wolter-I glass mirror substrates for x-ray reflectivity and scattering tests.

3.2 Installation of Mirror Segments into Module Housing

Once mirror segments are fabricated and properly inspected and measured so that they are qualified both optically and mechanically, a large number of them, ~100, need to be aligned and bonded into a housing to form a module.

3.2.1 Alignment

The alignment process **locates** and **orients** a mirror segment into its design position and orientation so that it works together with other mirror segments (Evans et al. 2011). Since the mirror segment is thin and extremely flexible, it is first placed onto a stiff holder that supports the mirror at three locations and with its optical axis close to the vertical direction to minimize gravity distortion. This holder effectively converts the flexible mirror segment into a rigid body. Thereafter, the mirror segment is moved and aligned with the holder.

The precise location and orientation of the mirror segment is achieved by a computer-controlled hexapod under the guidance of a Hartmann sensor that interrogates the mirror segment meridian and meridian to determine its overall location and orientation (Saha et al. 2011). This location and orientation information is fed into, and processed by, the same computer that controls the hexapod, achieving closed-loop operations. As of October 2011, the alignment of a mirror segment can be achieved in less than an hour, making it possible to finish the alignment and bond a mirror segment in less than 4 hours, meeting the requirement of an IXO production schedule.

3.2.2 Permanent Attachment

Once the mirror segment has been manipulated into the correct location and orientation, it is permanently attached to the module housing. The permanent attachment process is illustrated in Figure 5. It begins at the end of the fabrication process when six clips are adhesive-bonded to each mirror segment's two edges, shown as gray half-moons. These clips, serving as bonding pads and having been shown to not cause any unexpected figure distortion, will help distribute stress to ensure that the maximum local stress is well below the ultimate strength of the glass. These clips are part of the mirror segment delivered to the alignment and integration process. The first step of the bonding process is to attach, with an adhesive, a pin to the clip. The pin is inserted through, and guided by, a bushing that is part of the module housing. As the adhesive cures, the pin may be moved by the shrinkage that is usually part of the adhesive cure process. After the adhesive fully cures, the pin is locked into the bushing with another adhesive that wicks easily into the clearance between the bushing and the pin.

We have successfully bonded mirror segments this way multiple times and consistently achieved x-ray images better than 10 arcseconds HPD at 4.5 keV, proving viability of this approach. We are in the process of optimizing the many parameters of this approach, including the following:

1. The size of the clip to strike a balance between the desire to adequately redistribute stress and the desire to minimize effective area loss due to these clips;
2. The adhesive bonding the clips to the mirror edges;
3. The diameter of the pin with respect to the size of the bushing to strike a balance between the minimization of friction and the minimization free play to achieve highest bonding accuracy;
4. Adhesive that locks the pin to the bushing: cure time, final strength, and outgas properties.

We expect to finish the optimization process some time in 2012 and proceed to co-align and bond multiple pairs of mirrors into a single module housing.
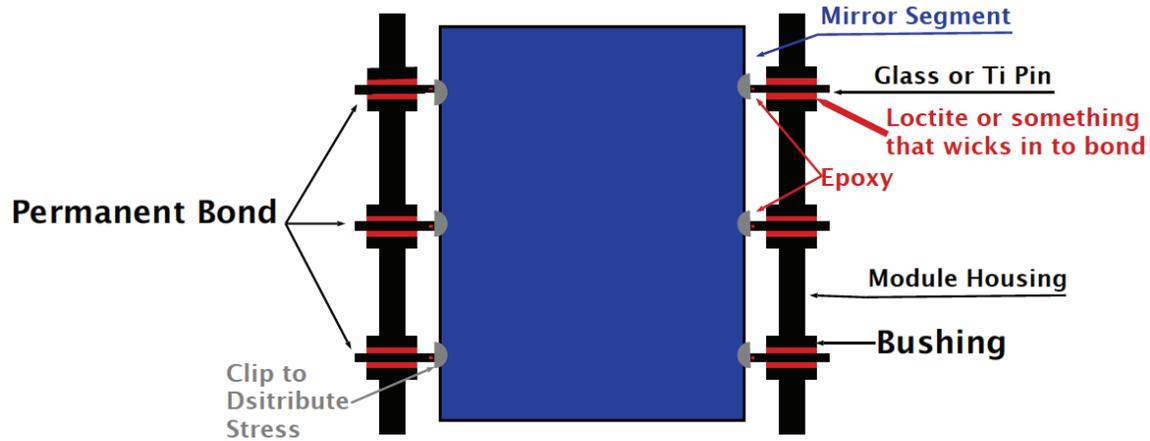

Figure 5.—Diagram illustrating the way a mirror segment is permanently bonded to the module housing. See Section 3.2.2 for details.

3.2.3 Module Construction and Systems Engineering

After the mirror segments are fully qualified and the procedures of aligning and bonding mirror segments developed and tested, the next step is to construct a mirror module to demonstrate that all these components and procedures work together with intended results (McClelland et al. 2011). Figure 6 shows the natural progression of our development effort, from a mirror housing simulator to a mini-module and then to a high-fidelity module that will fully validate this technology at TRL-6. During this progression all requirements on a module are progressively imposed and met.

The first requirement is performance: the finished module must meet angular resolution and effective area requirements defined in Table 2. In order to test a module with its optical axis in the horizontal direction, the mirror segments must be bonded in a geometry engendering the minimal distortion. Detailed finite element analysis has shown that mirrors bonded the way as described in Section 3.2.1 does meet this distortion requirement for a 5 arcsecond telescope system when the housing is sufficiently stiff.

The second requirement is that the module must be able to withstand launch loads. While accurate dynamic analysis can only be obtained when the spacecraft design is known, we have assumed a close to worst case scenario to ensure that the way we construct the modules are valid for virtually every conceivable spacecraft design. Detailed finite element analysis under the worst case scenario has shown that the mirrors attached at the six locations indeed can withstand loads imparted by an Atlas-V vehicle. This conclusion will be tested multiple times in coming years as we construct modules of progressively higher fidelity.

The third requirement is that the module must be able to achieve specified imaging quality in a realistic orbital thermal environment. There are two aspects to this requirement: One is bulk temperature, the other thermal gradients. We have determined that the module housing and the mirror segments will have similar coefficients of thermal expansion (CTE) to minimize any effect that can be caused by any bulk temperature change from ground to orbit. Extensive thermal analysis has shown that, given the D263 glass's relatively large CTE and low thermal conductivity, maintaining a thermal environment to guarantee 1-arcsecond imaging performance may be very challenging. With silicon being the mirror material, however, the situation can be orders of magnitude better. This is because silicon's CTE is about half that of D263 glass and its thermal conductivity is two orders of magnitude larger. Everything else being equal, it is much easier to maintain thermal equilibrium for a telescope made of silicon mirrors than glass mirrors.

Figure 6.—Three types of modules depicting the progression of our technology development. Left: a mirror housing simulator to which single pairs of mirrors are aligned and bonded; Middle: an expanded view of a mini-module that contains three co-aligned and bonded mirror pairs; Right: a high-fidelity module that has tens of to hundreds of mirror segments aligned and bonded.

The fourth major requirement is that we must understand quantitatively how gravity release will affect the imaging quality on orbit. We will understand this by developing finite element models that can adequately predict imaging performance at various gravity configurations. All these predictions will be quantitatively verified and the model fine-tuned such that the model's prediction of the on-orbit imaging performance is reliable.

4. Resources

The mirror technology development program outlined heretofore takes persistent effort of a dedicated team and consistent funding over many years to bring to fruition. In the past several years, this program has been supported by initially the Constellation-X and then IXO project office, GSFC IRAD, and APRA grants. While the moral support has always been very strong and consistent, the funding support has fluctuated wildly from year to year, causing disruption in maintaining a cohesive team and continuity and thereby slowing down progress. We hope that in coming years the funding situation will be more stable, facilitating better planning and faster progress. Every dollar invested in this program now will be paid back manifold during the project implementation phase.

We estimate that we would need approximately \$3M a year between now and 2019 to achieve TRL-5 for building sub-arcsecond x-ray telescopes, enabling a sub-arcsecond flagship mission in the 2020's. This level of funding will sustain a level of effort consisting approximately 10 people with a skill mix of scientists, engineers, and technicians while allowing small procurement contracts to work with industry to develop partners who could eventually implement these technologies to build the telescopes. We envision the following milestones:

1. TRL-5 for building 10-arcsecond telescopes by 2012,
2. TRL-5 for building 5-arcsecond telescopes by 2014, and
3. TRL-5 for building 1-arcsecond telescopes by 2018.

In addition, this effort requires approximately \$3.5M one time funding in the early years to construct a vertical UV (wavelength~130Å) beam with appropriately multi-layered normal incidence optics and a vacuum system. This beam facility will be essential in testing mirror modules for performance, both angular resolution and effective area, as well as for diagnosing problems to facilitate the development of better x-ray optics.

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