Technology requirements for a square meter, arcsecond resolution telescope for x-rays: the SMART-X mission

Daniel A. Schwartz[a], Ryan Allured[a], Jay A. Bookbinder[a], Vincenzo Cotroneo[a], William R. Forman[a], Mark D. Freeman[a], Stuart McMuldroch[a], Paul B. Reid[a], Harvey Tananbaum[a], Alexey A. Vikhlinin[a], Raegan L. Johnson-Wilke[b], Susan E. Trolier-McKinstry[b], Rudeger H. T. Wilke[b], Thomas N. Jackson[b], J. Israel Ramirez[b], Mikhail V. Gubarev[c], Jeffery J. Kolodziejczak[c], Stephen L. O'Dell[c], and Brian D. Ramsey[c]

[a]Smithsonian Astrophysical Observatory, 60 Garden St., Cambridge, MA 02138, USA;

[b]The Pennsylvania State University, Materials Research Institute, University Park, PA 16802 USA;

[c]NASA Marshall Space Flight Center, Astrophysics Office, Huntsville, AL 35812, USA

ABSTRACT

Addressing the astrophysical problems of the 2020's requires sub-arcsecond x-ray imaging with square meter effective area. Such requirements can be derived, for example, by considering deep x-ray surveys to find the young black holes in the early universe (large redshifts) which will grow into the first super-massive black holes. We have envisioned a mission, the Square Meter Arcsecond Resolution Telescope for X-rays (SMART-X), based on adjustable x-ray optics technology, incorporating mirrors with the required small ratio of mass to collecting area. We are pursuing technology which achieves sub-arcsecond resolution by on-orbit adjustment via thin film piezoelectric "cells" deposited directly on the non-reflecting sides of thin, slumped glass. While SMART-X will also incorporate state-of-the-art x-ray cameras, the remaining spacecraft systems have no requirements more stringent than those which are well understood and proven on the current *Chandra* X-ray Observatory.

Keywords: Adjustable x-ray optics, x-ray telescopes, x-ray observatories, x-ray astronomy

1. INTRODUCTION: SCIENCE DRIVERS

SMART-X will be a major observatory, used by astronomers all over the world, with observations selected by peer review. It will be used to observe every kind of known astronomical system, and to contribute to all areas of astrophysics research. Trying to optimize an observatory for all such possible objectives would lead to over-complex and even contradictory requirements. We have derived the key requirements by focusing on a few major scientific problems, as defined by the 2010 decadal survey of astronomy and astrophysics.[1] SMART-X will be particularly well adapted to pursue scientific investigations[2] ". . .searching for the first stars, galaxies and black holes;" and " . . .understanding of the fundamental physics of the universe," as defined by that study.[1] It is unlikely these problems will be solved by the end of the 2020's, as they are not accessible to any other x-ray mission currently being prepared.

The Sloan Digital Sky Survey (SDSS) has detected many quasars at redshifts z≈6, when the universe was about a billion years old. These quasars must have a masses of 10^9 times that of our sun ($1M_\odot = 2 \times 10^{33}$ gm) in order to be radiating at the observed luminosities. It is expected that the first stars, galaxies, and black holes formed in the redshift range z=10 to 20, based on the epoch of reionization of the universe inferred from cosmic microwave background observations.[3] The SDSS quasars must have arisen from these first black holes, but it is problematical how they could have grown to such a large mass in only 10^9 years. If we trace them back to redshift 10 by assuming they accreted mass at the Eddington limited rate, they would have a mass of 3×10^4 $M_\odot$. Such objects might radiate at 30% of the Eddington luminosity in the x-ray band, which would be 2×10^{42} ergs
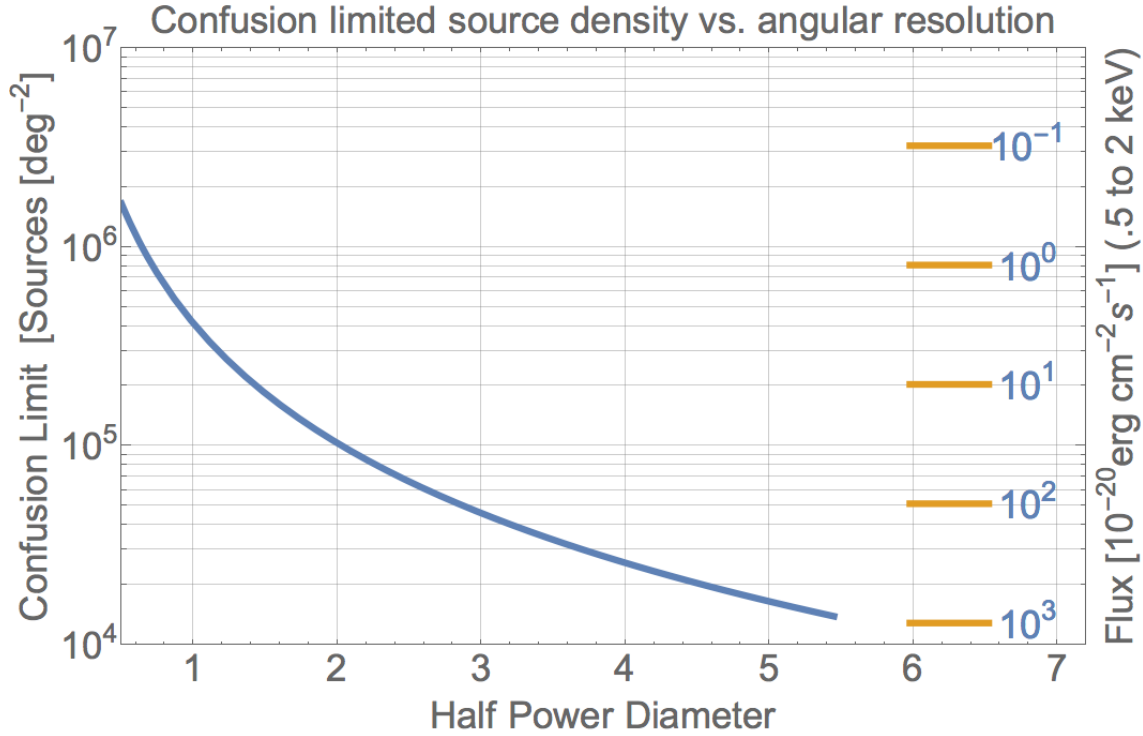
Figure 1. Confusion limit as a function of angular resolution. The blue line shows the maximum source density, above which individual sources cannot be reliably detected and located, as a function of the telescope angular resolution.[4] Abscissa is the half power diameter in arcsecond. The right hand ordinate gives the density of x-ray sources in the 0.5 to 2 keV band, corresponding to the given density in deg^{-2} of the left hand ordinate.[5] Note that the flux increases downward while the source density increases upwards.

s^{-1}, and the flux at earth would be 6×10^{-19} ergs cm^{-2} s^{-1}. The number density of x-ray sources at that flux level is about 70,000 deg^{-2}, so to overcome the confusion limit[4] requires an angular resolution of $2''.3$ half-power diameter at the edge of the useful field of view, as shown in Figure 1.

The off-axis aberrations of a Wolter-Schwarzschild design can achieve[6] this resolution up to about $12'$ off-axis, provided the on-axis figure quality is better than about 1 arcsecond. The actual on-axis resolution requirement should be similar to that of the *Chandra* Observatory, namely $0''.5$ half power diameter on-axis.

2. TECHNOLOGY AREAS

The design of an x-ray observatory can be classified into three major areas: the spacecraft systems, the x-ray instrument systems, and the x-ray telescope systems.

2.1 Spacecraft Systems

Major spacecraft functions include the pointing control; communications, command, on-board data storage and management; electrical power; thermal control; angular momentum management and propulsion; structures; mechanisms; software; safe modes; and radiation protection for the science instrument detectors. For SMART-X we expect these to have very similar requirements and implementation as for the *Chandra* mission,[7] primarily driven by the same angular resolution requirement of $0''.5$. In particular, alignment, stability, pointing control, aspect determination, ground and flight operations, ground software, data analysis software, thermal control, assembly and test are essentially the same. The power requirement will be increased from 2900 W (beginning of life) for *Chandra* to about 5000 W. This results since the 7 m^2 mirror area will radiate 1500 to 2000 W to

space according to the Stefan-Boltzmann law, with the uncertainty depending on the efficiency of the thermal pre-collimator. We anticipate an increase of about 200 kg for the science instrument module, and an increase in the average data rate from 32,000 bps to 1 Mbps. We benefit from an overall decrease of the mirror mass assembly from about 1600 kg for *Chandra* to about 1100 kg for the SMART-X design we will be presenting.

The actual cost of SMART-X development and operation should therefore be the same or somewhat less than that of *Chandra* in same year dollars.

2.2 X-ray Instruments

The x-ray instruments detect and measure the position, energy, and arrival time of individual x-ray photons. Transmission or reflection gratings may be inserted or removed from the optical path, to disperse the incoming x-ray beam allowing energy resolution $E/\Delta E \geq 4000$, below 2 keV.

The science instruments will most likely be procured via a competition to carry out a specific program of astrophysical observations. We can anticipate functional requirements to cover a $20' \times 20'$ field of view, to oversample the $0''.5$ resolution of the telescope, and to provide a very large dynamic range of photon counting rate, $\leq 10^{-5}$ to ≥ 10's of counts per second.

Many groups have independently been working on such state-of-the art instruments[8–11] as candidates for previous mission concepts such as Constellation-X (CON-X), the International X-ray Observatory (IXO), AX-SIO, and ATHENA. The payload concept could include a microcalorimeter array,[12] critical angle transmission gratings,[13] off-plane reflection gratings,[14] and large format self-triggered CMOS arrays.[15]

2.3 X-ray Optics

The critical technology need for SMART-X is large area, light-weight, half-arcsecond resolution mirrors. Our group has been pursuing adjustable x-ray optics to realize such a mirror. A suite of technologies are needed. Light weight and large area are achieved by using multiple, concentric shells of very thin glass sheets, coated with a high atomic number material such as iridium for good reflection efficiency up to about 10 keV. The thin sheets cannot be ground to shape as in conventional optics, but instead are thermally formed, "slumped," to the desired shape on a figured and polished mandrel. Since such flimsy glass pieces could not be expected to hold a rigid shape through launch, the mandrels are not required to be of the final $0''.5$ figure quality. Optical metrology assesses the detailed figure of each piece as removed from the mandrel. The key innovative technology is then to develop a technique to adjust the mirrors to the final required shape. Our group at SAO has been pursuing in-plane bi-morph piezoelectric actuators to effect this adjustment.[16]

3. ADJUSTABLE X-RAY OPTICS

Figure 2 shows a straw-man concept of the mirror assembly. Individual modules (left panel) are aligned and mounted to form a 3 m diameter mirror. The mirror consists of 292 concentric shells with 0.4 mm thick glass sheets coated with Ir and formed to the required Wolter-Schwarzschild prescription for each primary/secondary pair. The reflecting pairs are aligned to each other within a module that spans 15° to 30° azimuthally. The assembly concept has heritage from the Con-X and IXO studies, but with the ability to adjust the mirror element shapes we expect to only require one mandrel for every two or three shells. Because further figure adjustment is accomplished after mounting and aligning each pair, the alignment process is allowed to impart some small distortion. Ground induced effects, such as gravity release, are calculated via finite element analysis, and will be verified by optical metrology measurements at different orientations to vertical. These calculated effects will lead to a final small adjustment to the piezo voltages to be applied on-orbit.

Simulations show that the figure correction can be done to the required sub-arcsecond precision, if the initial mirror figure is as good as 10 arcsec.[17] For a given pattern of actuators, we start with a finite element analysis (FEA) to predict the influence function of each actuator on the entire mirror piece.[18] We have used optical metrology to verify the accuracy of the FEA. For the simulation, we used a model of an actual mounted mirror that gave a $10''$ image. We considered 5 different azimuthal positions. Figure 3 shows the radial displacement as a function of axial position along those 5 positions. On the left is the displacement from the required figure, as a function of axial position for the 5 different traces.
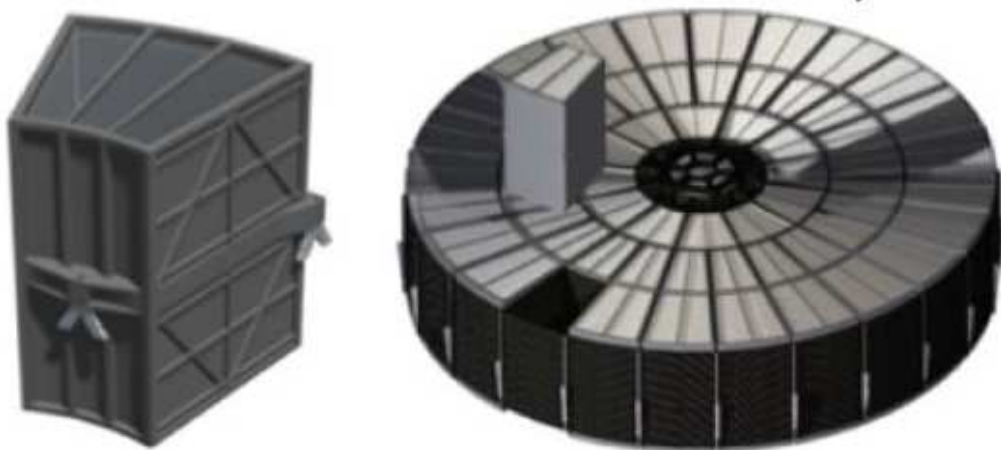
Figure 2. Mirror assembly concept. Primary and secondary glass pieces are aligned to each other, figured to a Wolter-Schwarzschild geometry, and aligned to about 90 other shells within a module (left). Discrete modules are aligned to each other and assembled within a 3 m diameter mirror structure (right). Not shown are the thermal pre- and post-collimators, and structure for attaching the mirror to the optical bench.
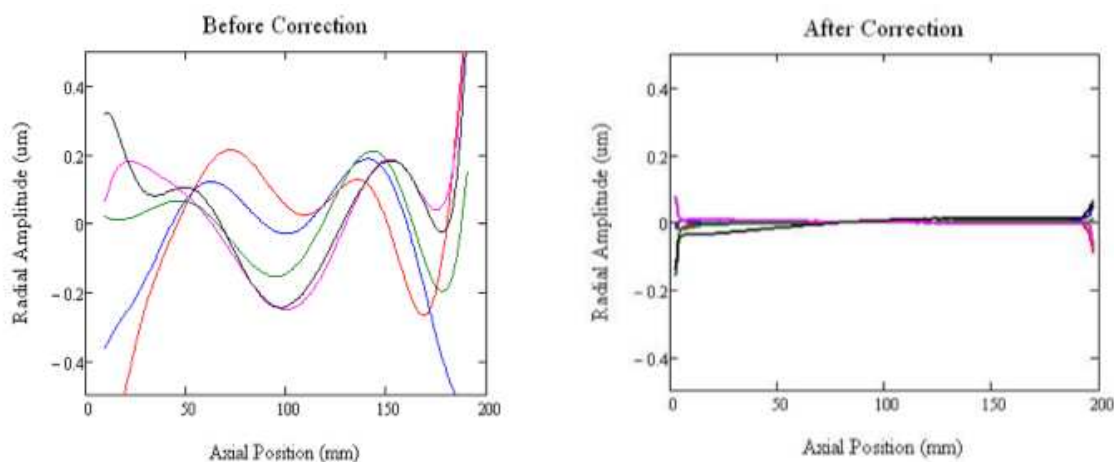

Figure 3. Using a bounded, constrained, least squares optimization we simulate the correction of one mirror element from an equivalent $10''$ (left panel) to $0.''4$ (right panel). Each figure shows the displacement from the required shape as a function of axial position, at five different azimuthal locations. Scales are the same in both panels.

The algorithm to optimize the figure takes some care. We directly minimize the slope errors, not the displacement errors. Because the piezo actuators can only squeeze more or less, but cannot expand, voltages can only be of one polarity, and cannot be so large as to exceed the strain capability of the piezo material, about 1000 part per million.

For simplicity in the error budgeting process we assume a Gaussian shape for the mirror point response function. For such a shape, the half power diameter of $0.''5$ corresponds to a root-mean-square (rms) diameter of $0.''74$. We budget using the rms quantity, since by definition it combines according to the root-sum-square law. The most important top level terms requiring technology development are the as-corrected figure, and the alignment. Smaller terms such as aspect reconstruction to $0.''2$ have been demonstrated on the *Chandra* observatory. The mirror figure terms are the low order figure, the uncorrectable figure errors due to upper mid-frequency and micro-roughness scattering, and any distortion resulting from the packing of the individual
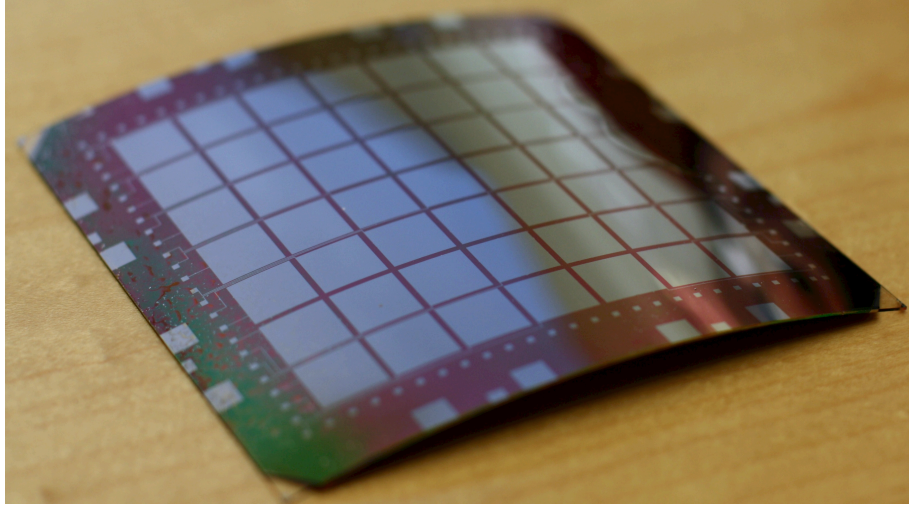
Figure 4. We have deposited an array of piezoelectric cells on cylindrical glass elements. The piece is 100 mm × 100 mm slumped to radius of curvature of 220 mm. There is an array of 7×7 piezo cells, of 10 mm × 10 mm size with 1 mm spacing in between. The x-ray reflecting side is face down in this figure. A discrete trace to each cell allows independent application of a voltage to induce local strain.

modules. The alignment terms include the metrology (for which we have achieved the required $0\rlap{.}''25$), the alignment process within a module, and the module to module alignment, each budgeted at $0\rlap{.}''25$. We take the gravity release term to be 10% of the size of the effect predicted from the FEA modeling, or less than $0\rlap{.}''1$.

We have successfully deposited piezoelectric films of $PbZr_{0.52}Ti_{0.48})O_3$ (PZT) on thin boro-aluminosilicate glass sheets. Initial efforts demonstrated the feasibility using flat Corning Eagle glass.[19, 20] Currently, we have taken a 100 mm × 100 mm sheet slumped to a cylindrical shape with a 220 mm radius of curvature, corresponding to one of the innermost shells of the mirror. RF magnetron sputtering was used to deposit an ≈ 1 to 2 μm thick piezo layer.[21] Figure 4 shows the resulting piece.

For our small test pieces we have been depositing traces to each individual cell, and connecting to an external wire providing a specified controlled voltage. We plan to carry out an x-ray imaging demonstration of a single mirror pair, using the NASA/MSFC stray light facility.[22] For that test we plan a 20×20 array of 5 mm cells, still with discrete wires. Voltages will be set via a computer driven controller. A prototype of our graphical user interface (GUI) is shown in Figure 5.

For the SMART-X mission with 8000 individual mirror pieces and 400 piezo cells per piece, discrete wires to each cell will not be practical. We expect to use a row/column addressing scheme so that we require as inputs the sum instead of the product of the numbers of rows and columns. To effect this, we have been demonstrating the feasibility of depositing ZnO transistors on top of an insulating layer over the backs of the piezo cells.[23] The concept is to make the electrical connections via anisotropic conductive film as is used in liquid crystal displays. We will also incorporate on-cell strain gauges which can be used to sense changes in the voltage/strain relation of the piezo material and facilitate any necessary on-orbit adjustments. Strain gauge response is also extremely sensitive to temperature, so these sensors may also play a role in the thermal control system for the mirror.

For the x-ray test of a single pair, we have designed a mount which conceptually can be extended to the flight configuration (Figure 6). In particular, the design is calculated to withstand the expected launch loads. The left panel shows the mounted pair, held by four supports on each edge. A custom designed hexapod manipulates the glass pieces prior to bonding. A laser beam is reflected off the piece to be aligned, and retro-reflected back to a centroiding detector assembly in a two pass Hartmann configuration. This concept was used to align the full shell *Chandra* mirrors within $0\rlap{.}''25$. To extend to the alignment of SMART-X, the shells would be aligned from the outermost to the innermost, since the reflecting surface must be exposed. The hexapod structure will be modified to allow access to the rear of each shell being aligned.
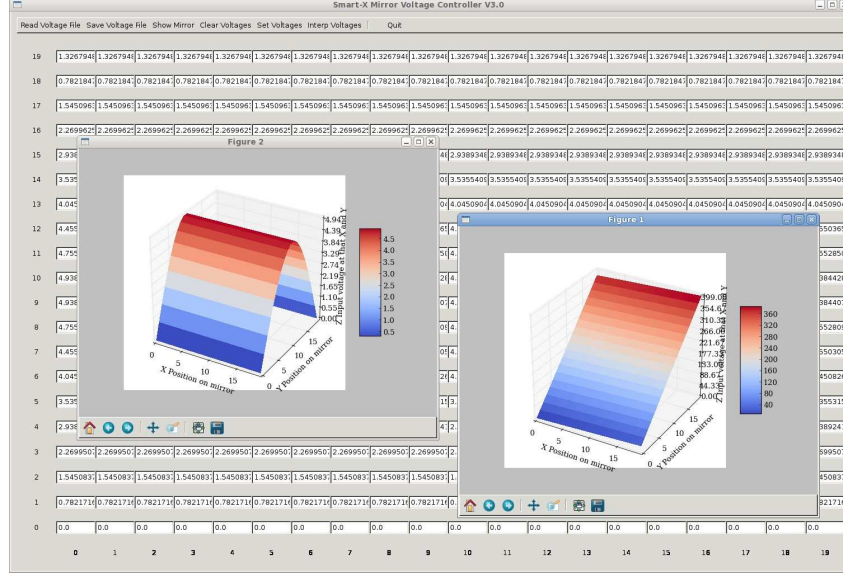
Figure 5. Prototype gui for controlling piezo voltages. The insert figures (not to scale) represent the current mirror figure errors as determined from optical metrology, and the predicted correction that will be applied when the piezo cells are activated with the 400 voltages shown in the background matrix structure. These voltages can be read in from a file, or individual cells can be directly addressed, and an existing set of voltages can be saved in a file.
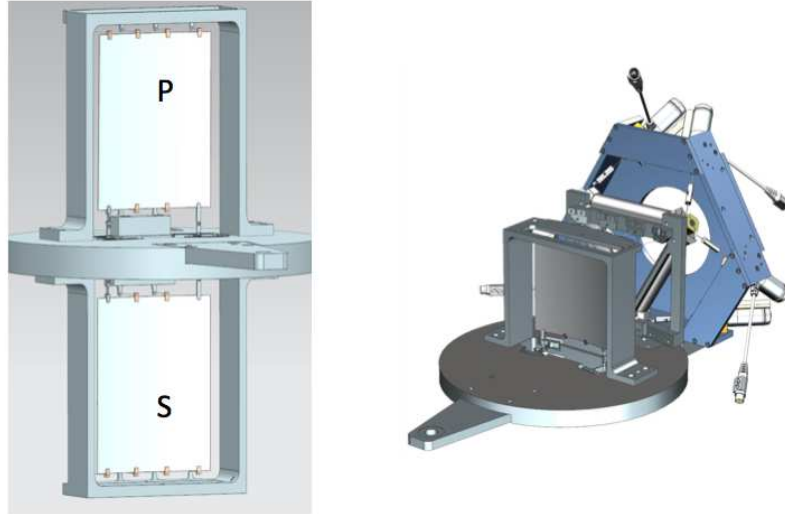

Figure 6. Alignment of a single primary (P) and secondary (S) mirror pair. Left panel shows the mounting fixture, holding each piece at four points top and bottom. Right panel shows the custom designed hexapod used for precise manipulation of the glass pieces prior to bonding to the supports. The system is designed to align with $0''.25$ equivalent rms diameter imaging. The concept is extensible to a full mirror module, aligning successively from the outermost to innermost pairs. We are looking at the x-ray reflecting surfaces in both panels.

4. SMART-X

We expect to verify the capability to figure and align a single mirror pair via x-ray testing at the NASA/MSFC stray light facility. This will establish the two largest terms in the imaging budget at technology readiness level 4. With a factor of 100 increase in throughput at 250 eV, compared to *Chandra*, we expect SMART-X to be poised to carry out game changing observations of the universe at redshifts 10 to 20.

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