Active X-ray Optics for Generation-X, the Next High Resolution X-ray Observatory

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ABSTRACT

X-rays provide one of the few bands through which we can study the epoch of reionization, when the first galaxies, black holes and stars were born. To reach the sensitivity required to image these first discrete objects in the universe needs a major advance in X-ray optics. *Generation-X* (Gen-X) is currently the only X-ray astronomy mission concept that addresses this goal. *Gen-X* aims to improve substantially on the *Chandra* angular resolution and to do so with substantially larger effective area. These two goals can only be met if a mirror technology can be developed that yields high angular resolution at much lower mass/unit area than the *Chandra* optics, matching that of *Constellation-X* (*Con-X*). We describe an approach to this goal based on *active X-ray optics* that correct the mid-frequency departures from an ideal Wolter optic *on-orbit*. We concentrate on the problems of sensing figure errors, calculating the corrections required, and applying those corrections. The time needed to make this in-flight calibration is reasonable. A laboratory version of these optics has already been developed by others and is successfully operating at synchrotron light sources. With only a moderate investment in these optics the goals of *Gen-X* resolution can be realized.

Keywords: X-ray optics, active optics, X-ray astronomy

1. INTRODUCTION

The high angular resolution of the *Chandra* X-ray Observatory has revolutionized X-ray astronomy, and indeed wide areas of astrophysics as a whole. At some point though, a larger and higher angular resolution successor to *Chandra* must be built (Fabbiano 1990, Elvis & Fabbiano 1996). Fortunately X-ray astronomy is nowhere near its physical limits: the Chandra mirror would have been diffraction limited at ∼20 milli-arcsec (van Speybroeck 2000, private communication), while the thermal line widths of 1 keV temperature plasmas are of order 100 km s^{-1}, so the 'thermal limit' to X-ray spectroscopy is $\lambda/\Delta\lambda \sim 6000$ (Elvis 2001).

More immediately, Chandra is a small telescope: The median exposure time for *Chandra* observations is a day (85 ksec), and many of the breakthrough observations needed 1 Msec (Table 1). This should not be surprising - the large number of independent spatial and spectral bins *Chandra* offers ($\sim 10^5$ in ACIS-I) requires large number of photons to fill them, but *Chandra* has an area of only ∼800 cm^{-2}, equivalent to a 30 cm diameter optical telescope. As a year contains only ∼20 Msec of net observing time, even at the high observing efficiency of *Chandra*, only a small number of these Megasecond-class programs can be carried out in a year, and only a limited number in the whole *Chandra* lifetime. A reconaissance of the X-ray sky at high resolution requires an faster observation rate.

In terms of angular resolution, *Chandra* often provides just one unique example of each class of object: e.g. the Crab nebula wisps, the Antennae galaxy merger system, the 'bullet' cluster 1E 0657-06 (Markevitch et al., 2004) Only by increasing angular resolution can we expand these samples: a factor 10 improvement increases the accessible volume 100 times for Galactic objects (as they lie in a disk), and a 1000 times for extragalactic objects (and for objects within 100 pc). At the faintest fluxes, where the first generation objects will be found, high angular resolution is required to make firm identifications with counterparts from JWST, ALMA or other next generation telescopes.

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Table 1. Some Chandra Breakthroughs

Chandra Observations			Implication	reference
X-ray background resolved to 10 keV	Ms	→	accretion luminosity of the Universe	Giacconi et al. 2001
Dark Energy measured		→	new constraints on new physics	Allen et al. 2004
No cooling flows in clusters		→	20-year puzzle solved; AGN feedback	David et al., 2001
Cooling fronts in clusters		→	build up of galaxies, clusters	Vikhlinin et al. 2001
Warm-Hot Intergalactic medium	Ms	→	'missing baryons' found	Nicastro et al. 2002
Multi-phase Winds from AGNs	Ms	→	AGN 'feedback' to galaxy formation	Kaspi et al. 2002
Ultra-Luminous X-ray Sources		→	intermediate mass black holes?	Fabbiano et al. 2003
Galactic center flares		→	Not so quiet Black Hole	Baganoff et al. 2001
Hot ISM abundances	Ms	→	SN yields, ecology	Fabbiano et al. 2004
Optically dull/X-ray bright galaxies	Ms	→	hidden active galaxies	Alexander et al. 2003
0.5c wisps in Crab		→	particle acceleration to near c	Hester et al. 2002

Ms: exposure times approaching 1 Msec (2 weeks) needed to make the discovery.

The need then is clear. To give some substance to the science goals we first describe briefly the first generation of black holes and their expected properties. Then we outline the *Gen-X* Vision Mission study - a just completed 2-year NASA funded investigation. We then address the question of active X-ray optics in some detail, to show that this is a feasible prospect.

2. KEY SCIENCE: THE FIRST BLACK HOLES

The epoch at which the first light was emitted following the Big Bang is now being pinned down quite closely. The Dark Ages, during which the temperature of the Big Bang radiation dropped below the point at which it could keep hydrogen ionized, were clearly over by z=6.4 (an Age of the Universe of 0.87 Gyr) as we see quasars, Gamma-ray bursts and galaxies already formed then. As quasars show high metal abundances at z=6, there must have been more than one generation of supernovae to create these metals by z=6, pushing the epoch of the first stars backward. In fact, the 3-year WMAP results (Spergel et al. 2006) show an electron scattering optical depth to the CMB that puts the first ionizing photons at z$\sim$11 (Age = 0.42 Gyr). Another argument requires the early formation of black holes: the quasars we know of at z=6 are some of the most luminous objects in the universe, and the Eddington limit requires that they have masses of $10^9\ M_\odot$ or more. But black holes seem highly unlikely to grow at a rate well above the accretion rate set by the Eddington limit, and so can only double their masses on the Salpeter timescale, 4.5×10^7 yr. The original seed black holes probably were no larger than a few 100 $M_\odot$ (Heger & Wooseley 2002), so they need $\sim$20 Salpeter times, $\sim$0.9 Gyr to reach their z=6 mass. At a redshift of $\sim$10 we should find the first black holes undergoing their most rapid growth.

How can we observe these objects? Ultraviolet emission is absorbed by the intervening intergalactic medium (IGM), and redshifting means that the universe is opaque to all UV and optical wavelengths out at z=10. The millimeter band is excellent to probe up to high redshifts, and ALMA will do this. However, at some redshift no molecules will yet have formed, so this band loses power before the first objects are reached. Only the radio (SKA), infrared (JWST) and X-ray (*Gen-X*) bands can reach back to this epoch, and only X-rays carry strong atomic features for atoms heavier than hydrogen.

What does it take to see black holes in X-rays during their first growth spurt? A $10^3\ M_\odot$ black hole radiating at the Eddington limit at z=10 has an X-ray flux of 10^{-20}erg cm^{-2}s^{-1} (0.2-2 keV). This is some 1000 times fainter than the faintest *Chandra* deep survey limit (in 2 Msec, HDF-N, Brandt & Hasinger, 2005). So an area some 1000 times larger than *Chandra*'s is needed to get a detection, i.e. $\sim$100 m^2. To distinguish these faint background sources from foreground z$\sim$2-3 galaxies requires a resolution significantly smaller than their diameters, i.e. $\sim$0.1 arcsec HPD. These and similar requirements, derived from a wide range of astrophysics, determined the basic parameters of *Gen-X*

3. THE *GENERATION-X* NASA VISION MISSION STUDY

The *Generation-X* mission concept was selected by NASA for study in its "Vision Mission" program in 2003. The PI of the study was R. Brissenden of the Smithsonian Astrophysical Observatory (SAO), and there were study team members from most of the major US institutions involved in X-ray astronomy, both hardware-oriented and observational (Appendix A). The study assumed a launch date of around 2020.

The Vision Mission study involved several elements:

1. the development of a comprehensive science case, by a large team of institutions, that clearly spelled out the flow-down of requirements for area, spatial resolution, field of view, background, timing and spectral resolution;
2. optics studies at SAO and GSFC;
3. detector studies at SAO and MIT;
4. mission architecture studies at the GSFC IMDC and the JPL Team-X facilities;
5. student studies of magnetically controlled formation flying (MIT), optical bench vibration modes (U. Puerto Rico), and of a Kirkpatric-Baez alternative optic approach (Colorado).

3.1. Instrument Complement

A large high resolution X-ray optic can feed photons to a wide variety of instruments, including those which have not been practical to fly before due to their photon-hungry nature, e.g. polarimeters (which need $\sim 10^6$ photons/data point). While *Gen-X* may well, and probably should, carry this class of instrument, there are three devices which *Gen-X* clearly needs to be an astrophysically versatile observatory:

1. *Integral Field Spectrometer:* Envisaged as a microcalorimeter array with 2 eV resolution. To cover a 1 arcmin field of view at 0.1 arcsec requires a 600×600 array;
2. *Wide Field Imager:* Envisaged as a silicon based device with ~100 eV resolution and a 10 arcmin×10 arcmin field of view implying 6 k×6 k arrays, with >12 k×>12 k being desirable to properly sample the PSF;
3. *High Resolution Spectrometer:* Envisaged as a reflection grating spectrometer reaching R=10,000 by means of a ruling density of 11,600 lines/mm.

A long focal length X-ray mirror has a large plate scale, 1.4 - 3.6 arcsec mm^{-1}. A 10 armin diameter detector then has an array size of order 50 cm. A large detector implies a large particle background per sq. arcsec, so background reduction measures must be carefully considered.

3.2. Two Mission Architectures

The two mission architecture studies looked at two distinct ways of achieving the required area (Figure 1): a '*Con-X*-like' approach of 6 multiple identical spacecraft with 8-meter diameter mirrors connected by a fixed optical bench to a detector system 50 meters away at the focus (studied by the IMDC), and a 'XEUS-like' approach of a single 20-meter diameter mirror and a separate free-flying instrument spacecraft at the other end of the 125-meter focal length (studied by Team-X).

The free-flying alternative has the advantage that only one set of instruments needed to be built, rather than six. Also, the mirror is expected to have a longer lifetime than the instruments, so the free-flying instrument spacecraft architecture gives the option of replacing the instrument suite with a new instrument spacecraft using automatic rendezvous, without docking. The free-flying architecture, however, has the challenge that the mirror-instrument separation must be actively maintained at all times. Simple mutual gravitational attraction will cause the two spacecraft to collide in a short time in the absence of active control. This is clearly an issue for safe mode design.

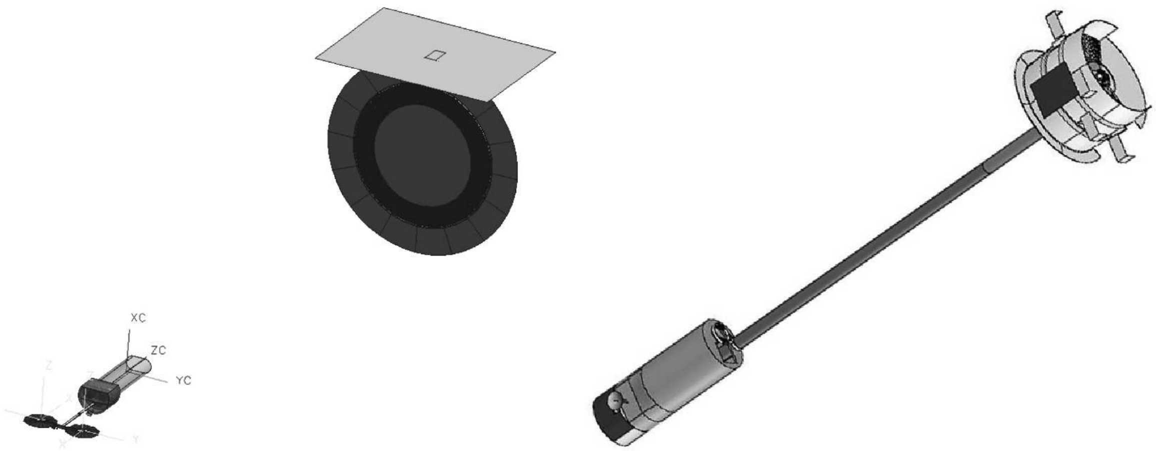

Figure 1. The two mission architectures considered for *Gen-X*: *left:* 20-meter diameter mirror with optics and detector spacecraft separated by 125 m (Team-X); *right:* 8-meter diameter mirrors in a set of single optic-detector spacecraft with 50 m focal length (IMDC).

3.3. Thermal Control of Optic

Going in to the study the thermal control of the mirror was a large concern, as the large mirror area must be unobstructed, and so is free to radiate to space, yet the mirror needs to be kept isothermal to ∼1 C, and within a range that does not overdeform the 20C figure formed on the ground beyond the scope of the active correction. Temperature maintenance could be attained by the use of capillary pumped loops and both constant and variable heat-pipes to conduct heat from a thermal collector on the heat/light-shield, solar panel side of the spacecraft. This has proved to be a robust, low power solution. The tolerances on the optical bench were acceptable, despite the 0.1 arcsecond resolution, due to the large plate scale implied by the long focal lengths.

3.4. L2 Orbit

The requirements for a constant thermal environment imposed by the active optics (see Section 4), the heat-pipe mirror heating scheme and the need for a low gravity gradient for these long focal lengths, all point to an L2 orbit for *Gen-X*. An L2 orbit was recommended by both studies.

A Delta IV-H launch vehicle is adequate for launching each of the 6 '8-meter' spacecraft and the detector instrument spacecraft of the '20-meter architecture to L2. The '20-meter' optics spacecraft however would require dividing the payload into at least two separate launches with assembly either in LEO or at L2. The '20-meter' approach imposes a launch window about 21 days wide for the instrument launch with respect to the optic, in order to match L2 orbits.

The telemetry requirement from L2 was not a major issue, although an enhancement of current DSN capabilities was assumed. *Gen-X* would generate an average of 400 Gbit of science data per day. Ka band transmission would require ∼1.25 - 1.75 hours/day of contact time.

3.5. Vision Mission Study

The Vision Mission study was completed and the report submitted to NASA in March 2006 and several NASA committees were earlier briefed on the results.

Both studies identified the X-ray optics as the main challenge to constructing *Gen-X*. The rest of this paper discusses this tall pole.

4. ACTIVE X-RAY OPTICS

The requirement for high angular resolution combined with low weight per unit area is tough. The 0.5 arcsec HPD *Chandra* mirrors weigh 18500 kg m^{-2}, the *Con-X* mirrors weigh 250 kg m^{-2}, while the 13 arcsec HPD XMM-Newton replica mirrors weigh an intermediate 2500 kg m^{-2}. An unsurprising trend of poorer angular resolution going with lighter weight is apparent. To break this correlation requires either a dramatic improvement in the manufacture of thin shell optics, or the approach adopted for the *Gen-X* Vision Mission study - the on-orbit correction of the optic figure by means of active realignment of small patches of the mirror shells - Active X-ray Optics.

Active X-ray optics involves adding substantial complication to the X-ray mirror system. However it comes with several advantages: the ground calibration of the mirror PSF can be reduced, the launch stability requirements can be eased, the operating temperature of the mirror need not be that at which the ground calibration took place (room temperature). Moreover, compared with the ∼10 Hz correction rate for adaptive optics on ground-based optical telescopes (needed to correct for the constantly changing atmospheric distortion of the incoming wavefront) X-ray optics only need adjusting on a months timescale, assuming a benign constant illumination orbit. The actual rate at which figure adjustment must be carried out in order not to consume excessive observing time must be of order days every few months (∼1%), so the rate is orders of magnitude slower than ground systems. To maintain almost constant illumination a baffle/sun-shade system larger than the mirror is required, and the sun-pointing direction angle must be restricted, e.g. to $\pm 15^\circ$ of 90°.

The clear disadvantage is that each 1 sq.m of collecting area at grazing incidence requires ∼100 m^2 of reflecting surface which must be controlled. If corrections need to be made on 10×10 cm patches this implies 10^4 actuators/sq.m collecting area. Depending on design choices this may rise to 10^6 actuators/sq.m (for 1×1 cm patches). The challenges then become: *sensing* the misalignments for all these sensors, *calculating* the adjustments to the figure that are required, and *applying* these corrections.

A 0.1 arcsec HPD implies axial figure errors comparable to *Chandra*, but azimuthal figure errors that are substantially tighter.

4.1. Piezoelectric Actuators

Ground-based optical systems for active optics use mechanical actuators that act on the rear of the mirror, perpendicular to the reflecting surface. While that approach works for normal incidence optics, such a system would cause significant problems with blockage of the optical path in the grazing incidence telescopes needed for broad band X-ray astronomy. Mechanical actuators also need lubricants, which would be hard to isolate from the reflecting surfaces in the grazing incidence geometry.

To overcome the optical path blockage problem we explored the possibility of applying thin piezoelectric actuators to the back side of the X-ray mirror shells. These act like a bi-metallic strip, bending one way or the other depending on the applied voltage. A pair of actuators oriented axially and azimuthally is needed for each patch to be controlled. The actuators can exert only moderate forces and so are a natural match to thin shell (∼0.2 mm) optics. Compared to mechanical actuators they have no hysteresis or backlash, which are clearly undesirable properties.

4.2. Finite Element Analysis of Piezoelectric actuators

We assume that the *Gen-X* mirror would be constructed from shells manufactured to a figure PSD tolerance similar to those of the *Con-X* shells (Figure 3). Several other technologies are being explored that may reach similar tolerances (Hudec et al. 2006, Gubarev et al. 2006, Friedrich et al., 2006), so we are not presuming a specific mirror manufacturing technology for *Gen-X*.

Beginning with *Con-X*-class optics, which have demonstrated good micro-roughness and mid-frequency figure above 0.05 mm^{-1}, the 0.1 arcsec HPD requirement for *Gen-X* implies correcting 0.4 μm azimuthal figure errors to 0.004 μm. We performed a finite element analysis that shows that this level of correction is attainable. Assuming 2 cm sized axial correction patches we obtain a PSD that is well corrected for scales larger than 0.025 mm^{-1}. Figure 4 shows how this compares with the *Chandra* PSD.

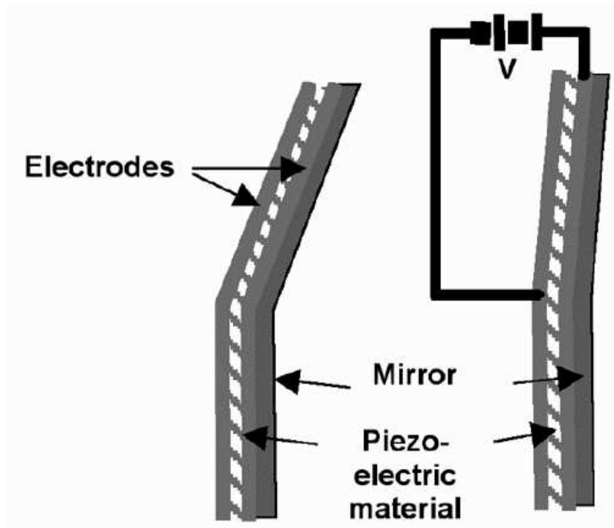

Figure 2. Arrangement of piezoelectric actuators on a Wolter I X-ray optic.

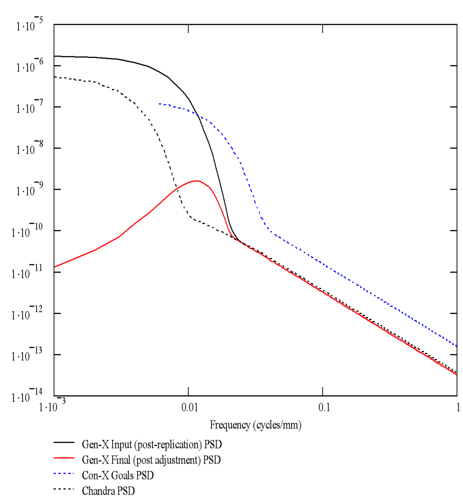

Figure 3. Power spectral density (power vs. frequency (mm^{-1}) for several mirror figures: the *Con-X* goal (light dashed), *Chandra* (heavy dashed), *Gen-X* pre-adjustment (heavy solid), *Gen-X* post-adjustment (light solid).

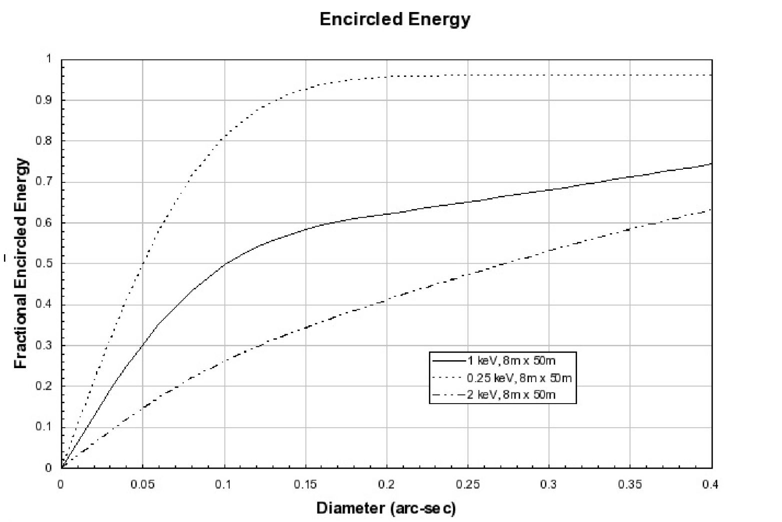

Figure 4. *Gen-X* encircled energy vs. radius curve for the 8 m dia. 50 m focal length design at three energies: 0.25 keV (dotted), 1 keV (solid) and 2 keV (dot-dashed).

The resulting PSF meets the 0.1 arcsec HPD goal at 1 keV (Figure 4) for a 8-meter diameter optic. The longer focal length 20 meter dia. optic has a less good PSF, due to the smaller graze angles involved. At 0.2 keV diffraction limits the HPD, while at 6 keV the smaller graze angle again degrades the PSF. This design is an existence proof. As yet no optimization has been done on this mirror design to broaden the energy range over which a 0.1 arcsec HPD can be obtained. Nor have we investigated the field of view over which this tight HPD is obtained, although scaling from Van Speybroeck & Chase (1972), suggests a ∼2 arcmin diameter.

4.3. Sensing Misalignments & Calculating Corrections: Out of Focus Imaging

Each actuator has to have radial, axial and tangential errors measured and corrected. Yet the on-axis focussed image contains nowhere near enough information to determine the misalignments of $\sim 10^6$ mirror patches.

To retrieve this information we explored the possibility of using out-of-focus images of the converging X-ray beam, thereby separating out information from every sector of every shell, and resolving each parabola-hyperbola shell pair axially. This factorizes the problem making it a weakly-coupled set of equations to solve, rather than a $(10^6)^2$ matrix problem. There is no coupling beyond the size of a single mirror sector.

The inspiration for this approach originated with the *Chandra* 'ring focus test' (Figure 5). (Similar tests have been performed for NeXT and InFOCuS, Ogasaka et al. 2006). The true ring focus would give a perfect thin ring for a perfect optic. Instead, for the control of active X-ray optics it is preferable to have different axial segments of the mirror pairs image to different locations on the detector in order to resolve them and measure their misalignments individually.

Placing an imaging detector ∼2% forward of the focus (∼2.5 m for a 125 m focal length), would create separate images of each shell and of each azimuthal parabola-hyperbola mirror pair segment. For example, consider a 20 m diameter, 125 m focal length mirror employing 10 cm sized active figure correction patches. There would be ∼300 azimuthal sectors in the outermost of the ∼ 300 mirror shells, and 10 axial segments per reflector (for 1 meter long reflectors). Putting a detector 2% forward of the focus would give annular images of the mirror shell annuli up to 40 cm in diameter. These annuli have widths of ∼4 cm so each image would be ∼400 μm thick at this location. These could be imaged into 20 axial elements with a 20 μm pixel detector, giving the required resolution of the mirror reflecting surfaces.

The "Wide Field Imager" (§3.1) has similar dimensions. In the '20-meter' architecture the separate detector spacecraft could readily move this instrument to the correct forward position. In the '8-meter' single spacecraft

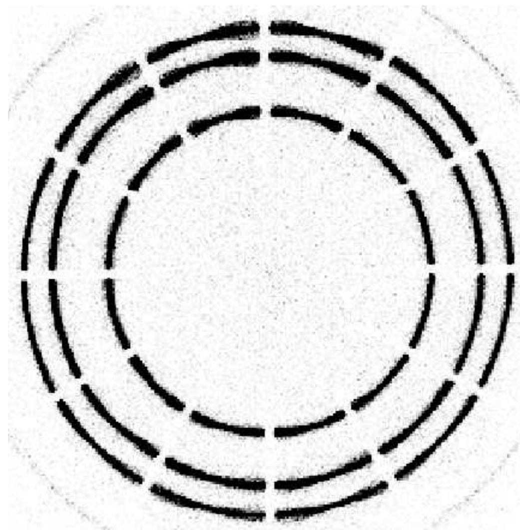

Figure 5. *Chandra* (AXAF) ring focus image. The detector was placed forward of the focus in the converging beam from the four mirror shells (only 3 are shown here), each of which produces a separate ring that is azimuthally resolved. For a perfect optic the true ring focus would yield pure circles for each shell. For an active optics application the detector would deliberately be placed where a radially extended image would form, imaging each axial segment of each shell sector separately.

option an axial translation stage would be needed. Whether the out-of-focus detector could double as a wide field detector at the true mirror focus, or whether a new special purpose detector that can be inserted into the converging beam as needed is required, should be the subject of a trade study.

Each square meter of effective area needs 100 m^2 of reflecting surface and so $\sim 10^6$ 1 cm patches. In order to make an accurate correction let us assume that a 3% precision is required for each patch and so a total of 10^9 counts m^{-2} of effective area. Is this feasible using celestial calibration sources? Sco X-1, the brightest persistent source in the sky, counts at 10^5 counts s^{-1} m^{-2}, while the second brightest source, the Crab Nebula, yields 10^4 counts s^{-1} m^{-2} and some 20 or so other sources count at 10^3 counts s^{-1} m^{-2}. As the number of actuated patches scales with the area, the length of an alignment observation is independent of the total mission area, and takes 10^4s - 10^6s$/A_{100}$, where A_{100} is the area of a patch in units of 100 cm^2. This is a reasonable time, and allows for several cycles of correction during each alignment campaign, unless the patches are small.

Calculationally, once the problem is factorized by the use of out-of-focus observations, the problem is not difficult in terms of CPU time. Keck adjusts 349 actuators at 10 Hz (van Dam et al. 2004). If we require that the calculation take no longer than the observation then we can operate at 10^{-4}Hz - 10^{-6}Hz, so allowing $349\times10^{5-6}$ correction calculations, comparable with the number of actuators, even assuming no increase in CPU speed.

There is a final degeneracy in the proposed scheme: the pairs of parabola and hyperbola patches are not separated. This separation could be achieved by deploying a finite focus calibration source flown as part of the *Gen-X* mission. For such a source illuminating the same parabola patch as a source at infinity, a different hyperbola patch would be illuminated. Positioned appropriately, the finite focus source might be able to created annuli in the gaps between those created by a source at infinity, so that the two observations could be carried out simultaneously. If the two sets of images overlap, then a detector with good energy resolution could be used to separate out an emission line from the finite focus source from the continuum dominated celestial source. An artificial calibration source might also provide a higher count rate for small patch mirrors. This concept needs further study for feasibility.

5. PIEZOELECTRIC BI-MORPH MIRRORS AT SYNCHROTRONS

During the course of the Vision Mission study for *Gen-X* we searched the literature for applicable related work. We found that a long term program of work at synchrotron X-ray light sources has made great progress in developing piezo-controlled active X-ray optics. The program was motivated by the need to illuminate small samples without irradiating their surroundings.

This program, led by R. Signorato (Signorato et al. 2001, 2004), has developed increasingly complex piezo controlled X-ray mirrors using a design of pairs of piezos acting oppositely, which removes temperature effects. As a result they call their designs 'Piezoelectric Bi-morph Mirrors' (PBMs). These have reached meter-long (by a few cm wide) scales and operate in the Kirkpatrick-Baez configuration. Hence they need to bend only axially. Up to 32 actuators are employed, using actuators as small as 2 cm, in a mirror now in use at the Argonne National Labs 'Advanced Photon Source'.

Signorato et al. find that they can reduce the figure error amplitude by a factor 15 on the scales they control, from 150 nm to 10nm rms, and further improvement is expected. The figure correction is stable over days and months. No anticlastic effect ('saddling') in introduced by the piezos.

To progress from the synchrotron mirrors to ones suitable for X-ray astronomy requires: adaptation to the 2-D distortions required for a Wolter geometry; techniques that allow deposition of piezos onto the back of finished optics (potentially); designs that accomodate the substantial number of control wires; scaling up of the process from 32 actuators to $10^4 m^{-2}$ and the associated questions of speed and cost of manufacturing.

The independent development of PBMs nonetheless substantially raises the technical readiness of the piezo-controlled active X-ray optics needed for X-ray astronomy and *Gen-X* in particular, and enable an accelerated program geared toward demonstration of a flight-ready optic.

6. CONCLUSIONS

The future of X-ray astronomy needs a high angular resolution successor to *Chandra*, with larger area. Such a mission would address a huge range of astrophysics, and in particular would open up one of the few spectral windows to the study of the very first stars, galaxies, and black holes.

Mission architecture studies show that such a mission is feasible, despite the long focal lengths (50 m - 125 m) and large diameters (6 m - 20 m). The tall pole is the development of lightweight high resolution X-ray optics.

Active X-ray optics, controlled with piezoelectric acuators, address the biggest technical challenge faced by the *Generation-X* Vision Mission concept. Piezos are a good match to the thin shells required by light-weight optics and to the need not to block the narrow optical path through densely nested Wolter optics. A 0.1 arcsec HPD image at 1 keV can be produced with 2 cm sized actuators. Out-of-focus imaging of the converging beam will allow figure errors on the individual patches on each sector of each shell to be measured independently, and celestial sources provide a sufficient count rate to make the measurements in a reasonable time. The parallization of the problem afforded by the out-of-focus technique reduces the compute time to a modest level. Meanwhile, independent work at synchrotrons has shown that 2 cm sized (1-D) actuators can be constructed, and work well and reliably, reducing figure errors in a Kirkpatrick-Baez configuration by large factors.

The *Generation-X* Vision Mission study has shown that the obstacles to creating large high resolution X-ray optics to go well beyond the capabilities of *Chandra* are far smaller than might have been thought. It has not escaped our attention that once high resolution, light-weight, X-ray optics are available, then they would be the mirrors of choice for most, if not all, X-ray astronomy missions. We believe that the rapid development of active X-ray optics by means of a quite moderate sized program, is both an urgent and a reasonable short-term goal for X-ray astronomy.

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APPENDIX A. *GENERATION-X* VISION MISSION STUDY STUDY TEAM

Table 2. *Generation-X* Vision Mission Study Team

Team Member	Institution
Roger Brissenden (PI)	SAO
Martin Elvis	SAO
Giuseppina Fabbiano	SAO
Paul Gorenstein	SAO
Paul Reid	SAO
Dan Schwartz	SAO
Harvey Tananbaum	SAO
Richard Mushotzky	GSFC
Rob Petre	GSFC
Nick White	GSFC
William Zhang	GSFC
Martin Weiskopf	MSFC
Mark Bautz	MIT
Claude Canizares	MIT
Enectali Figureoa-Feliciano	MIT
David Miller	MIT
Mark Schattenburg	MIT
Robert Cameron	Stanford
Steve Kahn	Stanford
Niel Brandt	Penn State
Melville Ulmer	Northwestern
Webster Cash	Colorado