DESIGN AND DEVELOPMENT OF THIN PLASTIC FOIL, CONICAL APPROXIMATION, HIGH THROUGH-OUT X-RAY TELESCOPE

NASA Grant NAG5-5268

Final Report

For the Period 7 April 2000 through 6 October 2001

Principal Investigator
Dr. Herbert Schnopper

February 2002

Prepared for:

National Aeronautics and Space Administration
Goddard Space Flight Center
Wallops Flight Facility
Wallops Island, VA 23337

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

The NASA Technical Officer for this grant is John C. Brinton, Code 810.0, NASA Goddard Space Flight Center, Wallops Flight Facility, Wallops Island, VA 23337

Light weight, thin plastic foil, X-ray telescopes

Herbert W. Schnopper*[a], Marco Barbera[b], Eric Silver[a], Russell Ingram[a], Finn E. Christensen[c], Suzanne Romaine[a], Lester Cohen[a], Alfonso Collura[b], Stephen S. Murray [a]

[a]Smithsonian Astrophysical Observatory, Cambridge, MA 02138-1516
[b]Osservatorio Astronomico di Palermo Giuseppe S. Vaiana, I-90134 Palermo, Italy
[c]Danish Space Research Institute, DK-2100 Copenhagen Ø, Denmark

ABSTRACT

We present results from a program to develop an X-ray telescope made from thin plastic shells. Our initial results have been obtained from multi-shell cylindrical lenses that are used in a point-to-point configuration to image the small focal spot of a an X-ray tube on a microchannel plate detector. We describe the steps that led up to the present design and present data from the tests that have been used to identify the properties of the plastic material that make it a suitable X-ray reflector. We discuss two applications of our technology to X-ray missions that are designed to address some of the scientific priorities set forth in NASA's long term plans for high energy astrophysics. One mission will observe in the 1- 10 keV band, the other will extend up to *ca.* 100keV.

1. INTRODUCTION

When compared with a far more massive, polished glass, high resolution optic, a telescope made from thin, metal coated shells yields a more efficiently filled aperture. Thin shell optics trade angular resolution for the advantages of increased collecting area (especially at higher energies), light weight and low cost. The combination of multilayering and thin shells that can be mounted close to the telescope axis will extend the useful energy range of a relatively short 5 - 6 m focal length telescope to 10 keV and that of a longer 8 - 10 m focal length telescope to > 100 keV. This approach has been adopted by several groups and a number of thin-foil technologies are being studied as candidates for the high energy optics for NASA's planned *CONSTELLATION-X* mission. Our work explores new and innovative plastic shell technology along a path not yet followed by others.

NASA's Structure and Evolution of the Universe Subcommittee's (SEUS) Roadmap 2003 - 2023[1] has identified a number of high energy astrophysics science goals. Many of these goals can be addressed by a light weight, low cost X-ray telescope of modest angular resolution (see **Section 3**). The X-ray telescope concepts we discuss below build upon ideas for thin plastic shell optics developed at the Smithsonian Astrophysical Observatory (SAO) (Schnopper[2]) and for multilayered Bragg reflection optics, originally developed at the Danish Space Research Institute (Schnopper[3] and Christensen et al[4]).

Our current program extends results already achieved within a pilot program that was started with seed funding from SAO. Additional support from the University of Palermo Observatory, the Danish Space Research Institute and a NASA Grant (NAG5-5268) provided the resources to demonstrate the basic features of thin shell, plastic optics. The key elements of our plan of work are:

- Analysis of the thermal and mechanical design of a unistructure X-ray optic made from thin, multilayer coated, plastic foils formed as full cones of revolution that are mounted as approximate Wolter I optics.

- Design and test of single and multilayered X-ray optical systems.

- Develop the specifications for high throughput X-ray telescope that are a good match to the detector arrays that are likely to be flown on future NASA X-ray missions.

*Correspondence: Email: hschnopper@head-cfa.harvard.edu; Telephone: 617 496 7763; Fax: 617 496 7577

When our plastic-foil technologies are successfully demonstrated, they will become candidates for NASA X-ray missions that require large collecting areas and modest angular resolution such as: *CONSTELLATION X (HXT)* ,part of an *ALL SKY EXPLORER*, and *a HIGH RESOLUTION SPECTRAL IMAGING MISSION*. The thin shell technology we discuss here was also part of two EXPLORER class proposals to NASA: The *X-RAY SPECTROSCOPIC EXPLORER (XRASE)*[5]and the *BALLOON BORNE NUCLEAR LINE EXPLORER (B-MINE)* [6,7]. We discuss these missions in **Section 3**.

We will first review the results from prior work, then present the details of the next phase of the program and, finally, discuss the applications of our technology to NASA's High Energy Astrophysics program

2. EXPLOITING THE ADVANTAGES OF PLASTIC SHELL TECHNOLOGY TO DESIGN, BUILD AND TEST A NEW TYPE OF X-RAY TELESCOPE.

We have identified a plastic foil material with a high quality surface smoothness (~ 4 - 6 Å) and with mechanical strength and thermal expansion properties appropriate for X-ray optics. These properties make it possible to consider innovative and unique approaches to telescope implementation that eliminate the more complex structure design used traditionally to mount and align thin-foil conical segments of either aluminum or thin glass which cannot be formed as complete truncated cones of revolution. Plastic shells can be formed as complete surfaces of revolution and we take advantage of this key property to use a lightweight "unistructure" to mount and align the shells accurately.

We have found it convenient to make cylindrical lenses in the early phase of our program. The entire reflecting surface of the lens can be illuminated by a diverging beam of X-rays and it will image a source on a surface that is equidistant from the center of the lens. A conventional analysis that leads to a point spread function and an encircled energy curve can be obtained. In addition, test results from a multi shell lens allows us to determine just how well the individual shells are co-aligned. During the next phase of our program, we will extend the testing to double refection optics created by mounting conical shells back-to-back. An important point at this stage of the program is that our lenses can be tested in relatively short beam pipes at grazing angles that are the same as those used to test conical approximations to Wolter 1 optics in much longer facilities. We are certain that with more development our point-to-point imaging lenses will meet the desired full width at half maximum (FWHM) and half energy width (HEW) requirements for potential X-ray missions and that Wolter 1 versions using the same technology will do so as well.

In addition to the most recent results, a number of tests on prototype optics have been obtained earlier during the SAO pilot program and we report them here as well. They characterize the surface roughness, reflectivity, scattering and imaging properties of individual pieces of foil and complete multi shell optics. Results acquired from a series of small learning steps will allow us to identify problem areas and develop solutions that will lead to a state of readiness to construct a Wolter 1, conical approximation, X-ray telescope.

2.1 Foil material

The ideal foil material for constructing X-ray optics should be inexpensive, readily available, mechanically stable, smooth, elastic, and uniform. The list of plastic foil candidates suitable for thin-foil X-ray telescopes narrows rapidly to a few proprietary plastics. We have identified one that has been shown to be easily deformed without losing its elastic properties or surface smoothness. To avoid thermal stress, the foils can be coated in a large chamber before being formed. Most important for potential industrial applications, they can be made into very small diameter (*ca.* several cm), free standing, full shells of revolution or spirals.

Traditional thin shell optical surfaces have been made from aluminum segmented (Al) foils. Although excellent progress has been made with this technology[8], the raw Al foil material is not inherently smooth. It must be either coated with a smoothing lacquer (as was the case for the *ASCA* and *SPECTRUM ROENTGEN GAMMA (SRG)* missions) or used as a carrier to replicate the inner surface of a smooth mandrel (as will be the case for the *ASTRO-E* mission). An alternative is the use of segmented thin glass plates that can be obtained with the appropriate smoothness[9] but are difficult to shape. Aluminum foils and glass plates can be formed into partial telescope shells by applying either mechanical force to the Al or heat to the glass. These materials can be stressed to the point that allows them to be deformed slightly while being mounted in the telescope structure. The use of Al or glass forces a segmented telescope structure and, therefore, a complex mounting procedure. Plastic optics offer the potential substantial cost and mass savings.

2.2 Coating the foils

State-of-the-art coating facilities are well established at SAO[10] and at DSRI (see **Section 8**). Single or multilayer coatings of C, Si, Ni, W and Pt have been deposited on test foils. In addition, the software necessary to design a coating and predict its performance over a wide energy range has been verified and is publicly available. A unique property of plastic foils is that they can be coated before being shaped. At the SAO multilayering facility, the foils are wrapped around the inner wall of the 65 mm diameter sputtering chamber. At this distance from the cathode, we can coat them with a uniform layer at a surface temperature that avoids damage. As a precaution against introducing surface stress, we coat the foil material on both sides. The thermal forming process that is used for glass foils would destroy the surface on pre-coated substrates. They must be coated after they are formed and this causes some production difficulties for the small diameter, innermost shells, of a telescope.

The various test facilities discussed in **Section 8** are capable of evaluating the coating over a wide energy band using both pencil and full beam illumination. Test results from coated and shaped foil samples demonstrate the robustness of the coating. Over a period of nearly two years, various test optics have been temperature and vacuum cycled in the course of transport to and test in beam line facilities. The imaging results obtained from tem are reproducible.

2.3 Shaping the foils

Plastic shells are formed as complete surfaces of revolution rather than individual segments. This feature allows a lightweight "unistructure" to be used to mount and align the foils accurately. We use vacuum hold-down mandrels to produce accurately formed cylindrical or conical shells of single or multilayer coated plastic foils. An example of a conical mandrel and free standing cones is shown in Figure 1. Before being mounted in the mandrel, we cut the foil to a length that will leave a small gap between the ends when the shell is formed. With the foil in the vacuum mandrel, we cut it to the appropriate width using the top and bottom of the mandrel as guides. We connect the ends with a thin, double sticky, plastic tape placed between a narrow strip of thin plastic material and the ends of the foil. We then weld this sandwich to complete a cylinder or a cone that then retains the form of the mandrel. In the future, we will study other procedures, including ultrasound, for welding the plastic strips into a figure that has a minimal deviation from the ideal one. When mounting the foils into the telescope structure, the welded area is placed behind a spoke to minimize the irregular area that is exposed to X-rays.

2.4 Holding the foils

We have made two different prototypes (see below) and tested them with X-rays. Both have a point-to-point imaging, single reflection, cylindrical optic geometry that is an approximation to a point-to-point imaging elliptical optic. This geometry is also a good, low cost, surrogate for studying the potential problems to be encountered in mounting and aligning many foils in an X-ray telescope. We can obtain images from a cylindrical optic in an inexpensive, short X-ray beam line facility, but images from a Wolter 1 optic requiring a large diameter, parallel X-ray beam, cannot.

2.4.1 Unistructure 1 Figure 2 illustrates the basic principles of the unistructure 1 design. It is a 175 mm diameter, 100 mm long, cylindrical lens. This device, is mounted with 20, tungsten (W) coated cylindrical shells. It was built at SAO in June 2000 and is defined by two spoked support wheels that are joined by a central hub and peripheral rods. Small holes are drilled into the spokes to accommodate fine pins that define the required figure for the reflecting surface of the shell. The plastic shells are constrained to the shape of the cage formed by the pins. In a zero g environment, the shell is in contact all along the pins. Since the accuracy of the pin locations defines the accuracy of the shell figure, this design allows the shells to be mounted without any accumulated "stacking error". The shell is, however, over constrained by the pins and the precision with which the parts are manufactured cannot be neglected. All the pin holes on each wheel are drilled in one session on the computer controlled milling machine. Since the holes can be located to a precision of 5 - 7 microns, the implied worst case mounting error is 15 - 20 arcsec for shells between 10 and 15 cm wide.

2.4.2 Imaging results from the unistructure 1 optic In July and September 2000, and again in March 2001, we tested a 20 shell cylindrical optic 175 mm in diameter in the 17 m X-ray Astronomy Calibration and Testing facility (XACT) at the Osservatorio Astronomico di Palermo "G. S. Vaiana" in Italy [11]. The shells were coated with 70 Å of W at the SAO multilayering facility. We attached the lens to an ALT-AZ mount that was equidistant (~8.15 m) between the X-ray source and a 40 mm diameter microchannel plate detector with 100 μm position resolution. At these large distances, the alignment of the telescope axis to the X-ray focal spot is critical. The point spread function (PSF) and encircled energy curves obtained at seven energies from C Kα (0.25 keV) to Cu Kα (8 keV) are shown in Figure 3 and the best Al K (1.5 keV) image is shown in Figure 4.

The 18-20 arcsec range of Full Width at Half Maximum (FWHM) measurements made in March 2001 are a factor of three smaller than those we obtained in March 1999 at the same facility from a unistructure mounted with only four shells. This improvement is due to a better selection of foils and a change in the central hub and wheel designs that allows the shells a more accurate alignment to the axis of the wheel. In addition, the encircled energy curves in Figure 3 are nearly identical, i.e., there is no energy dependent component that would be expected if the large encircled energy was due to small angle X-ray scattering from a surface with a characteristic roughness.

The half power diameters (HPD) of the encircled energy plots, however, did not show comparable improvement. An analysis of the integrated radial profile obtained from the imaging data yields an (HPD) of ~3.4 arcmin. We made a finite element analysis after the x-ray tests and it shows that, under a 1g lateral field, the upper half of the shell is not in contact with the support pins, while the bottom half sags between the support pins (Figure 5). Although the sides and bottom of the shell maintain contact with the pins, the bottom sags and only the sides have the appropriate figure. All portions of the shell are aligned parallel to the optic axis and this accounts for the narrow FWHM results. The well-aligned portion of the shell contributes to the narrow FWHM, but encompasses only about 1/4 of the total flux. X-rays that strike the drooping and sagging portions of the shell are reflected out of the central region of the image and cause the large HPD. Other considerations that we have not yet been included in the modeling are the strain in the shell caused by the W coating being on only one side and the stress of bending the foil into a cylindrical shape. Problems relating to the former can be eliminated by coating the foil on both sides. Future tests will be designed to elaborate on the latter.

We tested this distortion model by stepping a disk with a wedge-shaped beam limiter around the aperture of the lens and obtaining an image for each angular position. The results of such a test using a wedge with a 10 deg opening angle are presented in Figure 6.

The one g sensitivity presents an interesting problem. It may very well be that the pin and wheel design would work satisfactorily in a zero g environment. The only way to prove this possibility is to minimize gravitational effects and test the optic with its axis vertical. While this approach might be practical to implement for a small cylindrical optic that is designed for a short source to detector distance, it is likely to be very difficult to implement for a real, double conical approximation, Wolter I X-ray telescope. This consideration led us to consider unistructure2.

2.4.3 Unistructure 2, Model 1 Our second prototype design is an outgrowth of the results from the testing program for unistructure1 and draws upon the SAO experience with mounting the optics in the *CHANDRA* X-ray telescope. We built unistructure 2 to test a single 140 mm diameter, cylindrical, thin shell plastic lens. Instead of the shell being caged in a pin array, we cut a groove in each of the ribs of a single wheel to accommodate one edge of the shell. We attached a stiffener ring to the wheel to prevent gravitational distortion. The groove is slightly wider than the foil to allow for a buffer of epoxy glue on either side of the shell. In addition, we add a spacer plate to the mandrel which is removed after the shell is welded. It is slightly thinner than the depth of the groove in the wheel and allows for a buffer of glue at the bottom of the groove. The wheel assembly can be aligned to the axis of the mandrel by pins that also help guide the shell into the groove for gluing. Thus, the shell is trapped in the groove by the glue and retains the figure of the mandrel The completed optic is shown in Figure 7. A finite element analysis (Figure 8) shows that this approach will remove almost, but not all of the sag and droop and yield to a more accurate shell figure than the pin cage used for unistructure 1.

2.4.4 Imaging results from the unistructure 2, model 1optic_The first set of data, obtained with Al Kα (1.49 keV) is shown in Figure 9. The arcs seen are similar to those seen when there are axial alignment errors with respect to the source. Only a single arc appears when the 20 shell optic is misaligned and it can be removed with a succession of pitch and yaw adjustments. There are no arcs in Figure 4; the lens is properly aligned. The arcs seen in Figure 9 are indicative of off axis behavior that might be expected from the optic having a scalloped rather than a cylindrical shape. We used finite element analysis to model this effect. And the model yields a qualitative confirmation of the structure in the image. The level of thermal distortion obtained with the unistructure 2, model 1 lens was unacceptable and we designed a new model 2 optic with 32 spokes, each having half the thickness of those in the 16 spoke model (Figure 10).

All of the image data are subject to an uncertainty introduced by misalignment errors. With our present Alt-Az mechanism, it is possible to make yaw adjustments with a precision of 10 - 15 arcsec that are reproducible to about 20 arcsec. The pitch adjustments are made by turning a wire cable that has a considerable "windup" error and the pitch position is not reproducible. Pitch adjustments are made by trial and error with an accuracy of about 30 arcsec. We have designed a precision Alt-Az mount that is expected to be reproducible to 5 arcsec.

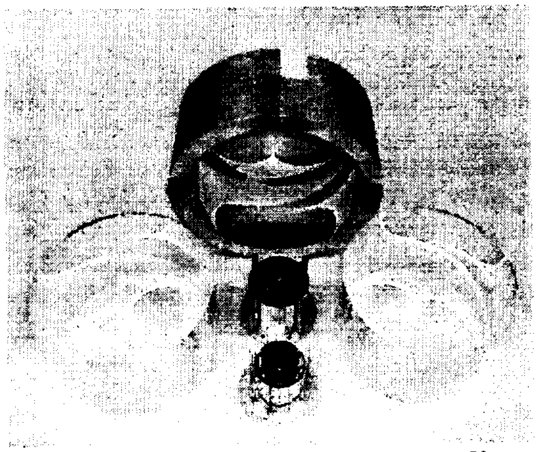


Figure 1. An Au coated shell mounted in a 150 mm diameter mandrel (top), free standing shells (sides), and a partially assembled 50 mm diameter cylindrical lens.

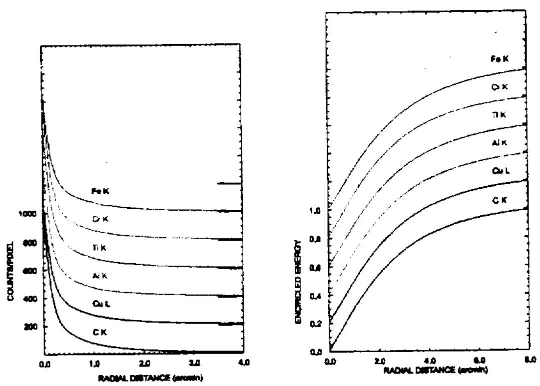


Figure 3. The radial profile (left) and enclosed energy (right) curves obtained with the unistructure 1 lens. The scales are set to the C data and the curves are offset for clarity.

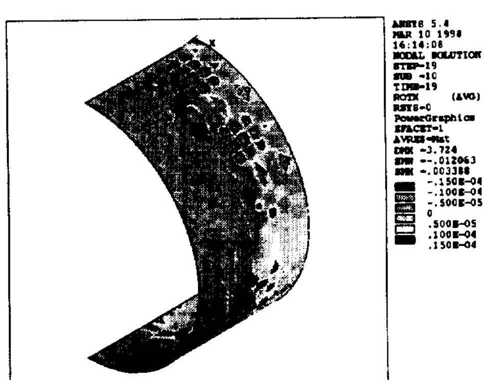


Figure 5. A finite element study of a single plastic shell constrained by 16 pins in a 1 g gravity field. Symmetry considerations allow only one half of the circle and one half of the length of the cylinder to be shown. Slope errors greater than ± 3 arcsec are shown in grey.

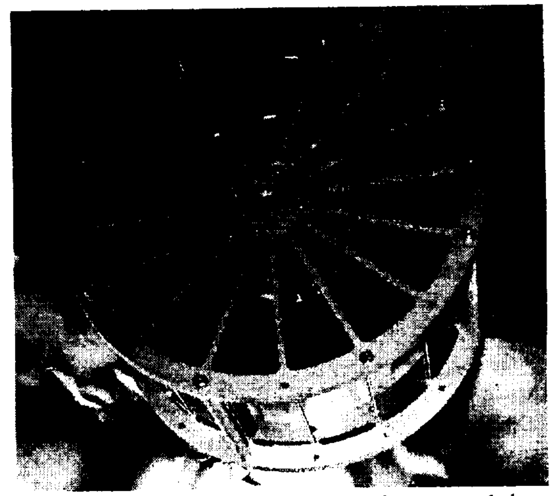


Figure 2. A 175 mm diameter unistructure 1 lens mounted with 20 W coated plastic shells. Some of the pins that define the figure of the outer shell are visible.

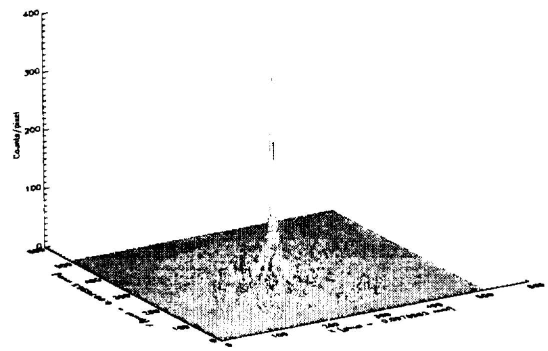


Figure 4. The best image obtained with the unistructure 1 lens at Al K (1.49 keV). The FWHM is 18 arcsec and the HPD is 3.4 arcmin.

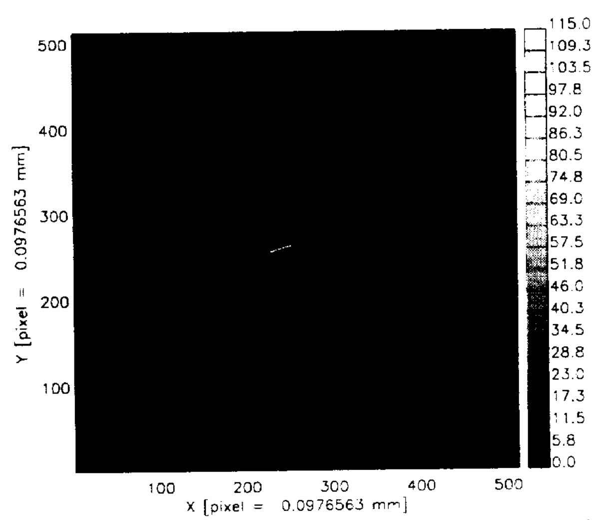


Figure 6. The best image obtained with the unistructure 1 lens with the input beam limited by a 10 deg wedge. The wedge is located at the center of the 22.5 deg sector that lies just below a horizontal plane passing through the center of the lens.

3. COMPARISON WITH OTHER TECHNOLOGIES

3.1 X-ray imaging data

Several groups are developing X-ray optical technologies that will meet the present and future requirements of NASA and ESA high energy astrophysics programs. It is of interest to compare the results obtained from our program with published results obtained by the other groups. The matrix in Table 3.1 is not well populated with published results, an indication that there is much work in progress. Except for full beam results for the optic shown in Figures 2 and 7 and presented in Figure 3 and 9, no full-beam, full-shell images have been published for thin shell optics larger than a few cm in diameter. Our best result, was obtained from the unistructure 2, model 1 lens for a 10 deg wedge shaped beam and is the one in Table 3.1. The radial profile and encircled energy curves are shown in Figures 15 and 16, respectively. We find a FWHM of 9.6 arcsec and an HPD of 90 arcsec.

3.2 Technology

Our mounting technology is discussed above in Section 2.4. Segmented optics, such as those developed for *ASTRO-E* and *SRG*, have shells that are suspended by ribs mounted radially in the segment structure and the shell figure is defined by grooves cut into the ribs. For the *HEFT*, the innermost conical foil segments of the optic are glued to spacers that have first been attached to a central hub and then machined to the appropriate conical figure. When the shell is complete, the next set of spacers is mounted on the non-reflecting side of the first shell segments and machined to accommodate the second conical shell, etc. The *CONSTELLATION-X* SXT optics require a very precise mount. The shells will first be accurately positioned in a reusable precision structure and then bonded onto the flight structure. Our unistructure 2 approach to mounting shells follows that of *CONSTELLATION-X* SXT and does not rely upon the support structure for the ultimate shell alignment precision as do *ASTRO-E*, *SRG* and *HEFT*.

4. RELEVANCE OF PLASTIC FOIL TECHNOLOGY TELESCOPE TECHNOLOGY TO NASA'S LONG TERM SCIENCE GOALS

4.1 A 0.5 - 10 keV multilayered telescope mission concept

The capabilities of a new generation of moderate angular resolution, thin plastic shell optics coupled with either a state-of-the-art microcalorimeter or CCD array form the basis of an explorer class mission, the *X-ray Spectroscopic Explorer* (*XRASE*) proposed by SAO. Results from the present optics development program described in **Section 2.4** show that a 2 - 4 arcmin HPD telescope is currently achievable and, with further improvements already foreseen, an HPD of <2 arcmin can be obtained. The telescope concept is a conical, Wolter I approximation, thin shell optic that benefits greatly from the unique properties of light weight, metal coated, plastic foils. We plan to multilayer the outer shells of the telescope to increase the high-energy reflectivity (see Figure17) for Fe K. An unusually wide variety of science objectives can be addressed by *XRASE*. The large effective area of the telescope and the high spectral resolution of the calorimeter would yield high signal-to-noise emission and absorption line measurements that can be used as diagnostics for temperatures, chemical abundances, ionization states, gas flow velocities, and turbulent velocities that occur in a range of the hot, X-ray emitting, plasmas that occur in objects from stellar coronae to the intergalactic medium in clusters of galaxies.

XRASE can also be used to search for absorption in the spectra of bright quasars and nearby clusters. Clusters are well suited for this project, since they reside at the dense intersections of filaments, which greatly increases the probability of a favorable line of sight along a filament. This study will probes the truly diffuse IGM. As an example, A85, a luminous cluster at z = 0.052 is known to have velocity structure along the line of sight and can be used to estimate the expected absorption. Hot gas within an over dense filament will retain the cluster redshift and will be photo-ionized by the Cosmic X-ray Background to produce absorption lines. A 30 Mpc distance corresponds to a Hubble flow velocity difference of 1500 km s^{-1}, which only broadens the O lines by about 3 eV. Simulated spectra for 200 ks observations from *XRASE* A 5σ detection of the O VII line would require a ~10^5 s *XRASE* observation. The simulations exclude the cluster cooling flow region, The blue bands denote 1 σ scatter. Thus, these low energy absorption lines should be narrow.

4.2 A 60 - 80 keV high energy nuclear line telescope mission concept

The *Balloon-Borne Microcalorimeter Nuclear Line Explorer* (*B-MINE*) is a mission concept that combines a high spectral resolution, small volume, low noise microcalorimeter with a multilayered, thin conical shell, approximation to a Wolter I telescope to reduce the background and enhance the effective area. A microcalorimeter with a Sn absorber and a Ge thermistor provides quantum efficiencies of 15% and an energy resolution of 50 eV at 68 keV.

Table 1. A comparison of data published by various optics development groups

Mission	Technology	S[a] or F	Test Results Energy keV	FWHM arcsec	HPD arcsec	BEAM[b] P/W/F
ASTRO-E[c]	epoxy replication on thin Al shells	S	0.5 - 12		~120[d]	F
HEFT/CON-X HXT[e]	thermally slumped thin glass shells	S	8, 28, 68		35[f]	multiple P
CON-X[g] (SXT)	thermally slumped thin glass shells	S			30[h]	W (~90 deg)
CON-X[i] (SXT)	mechanically formed Be shells	S				
XEUS	epoxy replication on thin Ni shells	S				
This paper	formed plastic shells	F	8	9.6[j]	90[j]	W (10 deg)

[a] Segmented or Full shell
[b] Full, Wedge or Pencil beam
[c] ASTRO-E Guest Observer Facility Web Page
[d] Full Wolter 1 telescope
[e] Christensen, *et al*, *Proc. SPIE* **4012** (2000), 626 - 638
[f] A stack of 5 cylindrical segments
[g] Petre *et al*, *Proc. SPIE* **4138** (2000), 16 - 24
[h] A single Wolter 1 α, 3α segment
[i] Petre *et al*, *Proc. SPIE* **4138** (2000), 16 - 24
[j] A single cylindrical shell

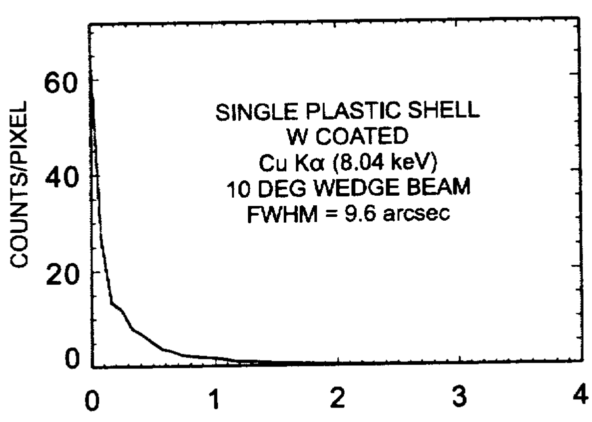


Figure 15. The radial profile obtained for the unistructure 2, model 1 lens for a 10 deg wedge beam.

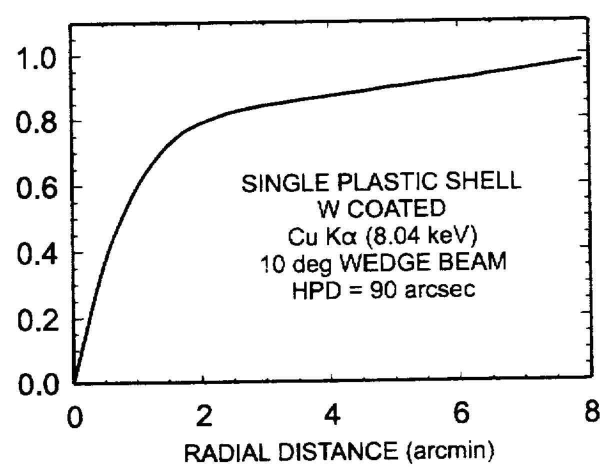


Figure 16. The encircled energy curve obtained for the unistructure 2, model 1 lens for a 10 deg wedge beam.

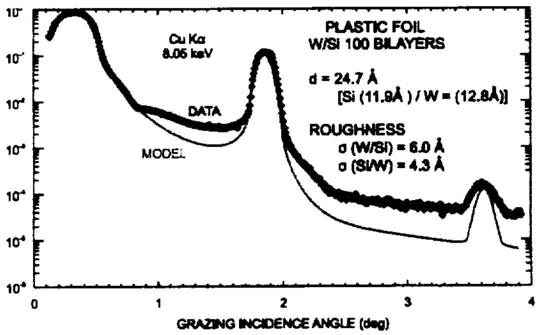


Figure 13. The reflection of Cu Kα X-rays from a W/Si multilayer deposited on a plastic foil. The sample holder is not able to hold the foil perfectly flat. It is necessary to open the receiving slit which increases the angular range and decreases the peak reflectivity. The integrated reflectivity is not affected.

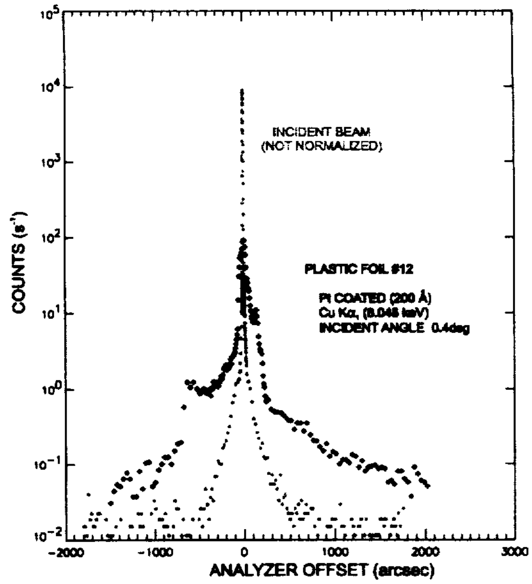


Figure 14. A Cu K scattering curve from a Pt coated plastic foil. The beam footprint on the sample is 20 mm. The peak has a FWHM of ~60 arcsec.

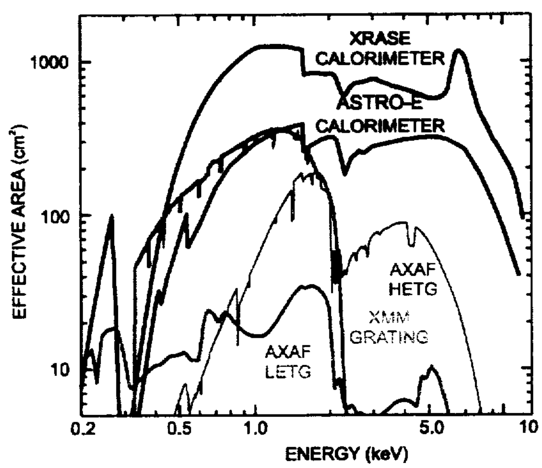


Figure 17. *XRASE* in the context of other high spectral resolution missions.

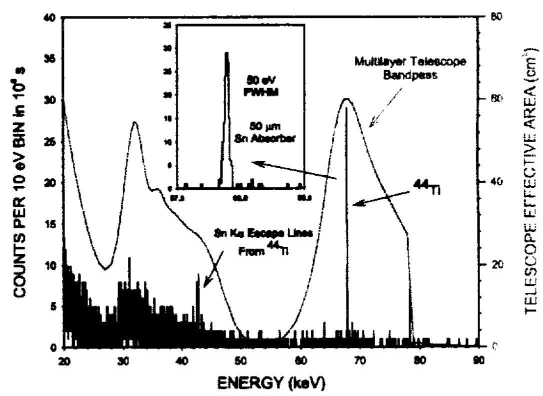
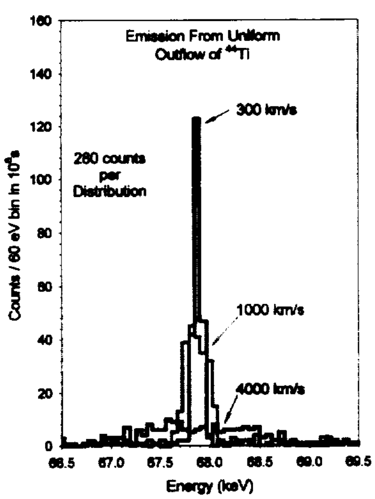


Figure 18. The effective area *vs* energy for the ***B-MINE*** telescope + microcalorimeter. The multilayers have been optimized for the ^{44}Ti emission line at 68 keV.



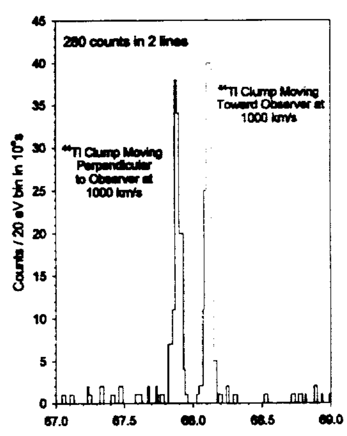


Figure 19 (left). Spectra of the ^{44}Ti 68 keV line modeled for an isotropic distribution of ejecta moving with various constant velocities away from the center. The high resolution of the microcalorimeter allows the line shapes to be measured to determine the velocity.

Figure 20 (right). Spectra modeled with the assumption that the ejecta move preferentially in direction. In one case, the ejecta appear to come from the center of the source at maximum blue shift. In the other case, it moves perpendicular to the limb at zero redshift. In that case, the direction taken in the disc cannot be determined.

While most applications of imaging optics are at relatively low energies, multilayered optics can provide a many order of magnitude enhancement in sensitivity over non-imaging technologies at energies approaching 100 keV (Figure 19). For *B-MINE*, we propose the use of Pt/C multilayers to enhance the reflectivity at 68 keV. This results in a peak effective area of 60 cm^2 and an FOV of four arcmin diameter (limited by the reflectivity of the multilayers). The outer shells also have a Pt/C multilayer, but are optimized for a band 25 - 45 keV to allow for more general studies of continuum radiation.

In this second mission concept proposed by SAO, the application of the new plastic foil technology to high energy X-rays is emphasized in the design of a *Balloon-Borne Microcalorimeter Nuclear Line Explorer* (*B-MINE*). This mission addresses two of NASA's primary science goals: the measurement of the mass distribution and velocity of ^{44}Ti in supernova remnants. These are familiar concepts and they serve to focus our thoughts on how to formulate a hard X-ray mission. When achieved, these results will lead to a better "understanding of the chemical evolution of stars and the exchange of matter and energy between stars and the ISM"[1]. The implications for SN explosions will "test physical theories ..., especially through investigation of extreme environments"[1].

Nuclear line astrophysics provides a direct probe of the details of one of the most violent events in the universe-- a supernova explosion that expels the heavy elements into the ISM from the nuclear furnace in which they were created. Because of its production deep in the stellar core and a 60-year half-life, ^{44}Ti provides a key diagnostic of supernova explosions. Although other elements are produced at high density and temperature in SN explosions, the key feature of ^{44}Ti is that its half life of 60 $\pm$ 1 yr is longer than the few years required for the overlying strata to become optically thin at high energies and sufficiently short that the ^{44}Ti remains localized around the SN site while it emits intensely. Thus, the nuclear properties of ^{44}Ti make it unique among all elements of nature for probing deep into the cauldron of a SN explosion.

A simple model of the ^{44}Ti emission from Cas A assumes a uniform outflow at a constant ejection velocity from the center of the explosion. The radius of the ^{44}Ti shell is given by the time since the explosion and the ejecta velocity. The flux from the limb (zero velocity in the line-of-sight) is enhanced compared with the flux from the center (limb brightening). Thus, the observed line emission will peak at zero velocity, with flux throughout the energy range corresponding to the maximum and minimum velocities. Figure 20 shows spectra that will be obtained for Cas A if the ^{44}Ti ejecta had velocities of 300, 1000, or 4000 km s^{-1}. If ejecta have a range of velocities, the spectra will be a sum of these simulations, with the line broadened.

With a spectral resolution of 50 eV, *B-MINE* can detect broadening if the velocity of the expanding ^{44}Ti shell exceeds 300 km s^{-1}. Detecting velocity broadening would provide clear evidence in for mixing of the ejecta layers, thus introducing new constraints on instabilities and transport mechanisms in massive stellar explosions. The high line detection sensitivity, arising from the large effective area, allows separation of individual knots at different velocities. For example, Figure 21 shows the simulated *B-MINE* spectrum of Cas A if the ^{44}Ti ejecta were in two knots, one moving toward the observer at 1000 km s^{-1} and the other moving perpendicular to the line of sight with the same velocity.

5. TESTING AND MULTILAYERING FACILITIES

For a complete understanding of the imaging properties of the thin plastic shell technology it is necessary to:

- Establish the X-ray reflecting and scattering properties of multilayered foil material.
- Establish the mechanical properties of the foil material.
- Form the foil material into complete surfaces of revolution.
- Mount the shaped foils in a suitable structure.
- Evaluate the imaging properties of the completed optic.

5.1 Existing facilities available to this program

Five facilities are used by us to evaluate the optical properties of the foils and the validity of the mechanical design of the conical optics. At SAO we have used an X-ray pencil beam facility to obtain small angle scattering data and a scanning electron microscope (SEM) facility to obtain: full beam images from small sized X-ray lenses with a microchannel plate detector, the broad band energy response of the lens to a continuum X-ray source viewed by a Si(Li) detector, and high resolution spectra from a line emission source viewed by a microcalorimeter. At the Danish Space Research Institute (DSRI) we use a high resolution X-ray facility located to measure small angle surface scattering from the foils. We have obtained additional surface roughness data at an atomic force microscopy (AFM) facility located at MIT. All of our full shell, full beam imaging results have been obtained at the XACT facility, located at the Osservatorio Astronomico di Palermo. It has a

17 m long X-ray beam line outfitted with a demountable X-ray tube and a microchannel plate imager. A well equipped and fully operational multilayering facility is currently in operation at SAO.

5.2 A new capability to be added at SAO
A 10 m beam pipe facility originally devoted to the ***CHANDRA*** program, is now available to this program and is currently being outfitted. An X-ray tube can be mounted at one end. The 10 m length will allow point - to - point images to be made with single reflection optics at C K (0.280 keV) and Al K (1.49 keV). There are plans to extend the beam pipe length to 40 m. When completed, the facility will allow testing over the entire energy range of interest to our program with lense up to 20 cm in diameter.

6. CONCLUSIONS

Tests on single- and multilayer coated plastic foils and on prototype models of complete optics have produced the following results:

- AFM results from a sample of uncoated foils yielded a surface roughness of ~4-6 Å.

- AFM data yield a surface roughness of 3.7 - 6.8Å which is compatible with X-ray reflectometry measurements of the interlayer roughness of 4.3 - 6.0 Å on multilayered foils. A strong relationship with the manufacturer is aimed at providing smoother material.

- Individual shells mounted in a mandrel reflect a pencil beam without significant broadening.

- Plastic foils are capable of accepting single or multilayer coatings that remain stable and achieve the expected reflection efficiency.

- Images obtained from the 175 mm, 20 shell cylindrical optic demonstrate that the proposed telescope structure is capable of being built to mount the foils with the accuracy and stability required to achieve a <2 arcmin mechanical design specification for an X-ray telescope.

- Initial tests on a single central wheel structure have been used to evaluate a new shell mounting technology based upon a single wheel with grooved spokes that allows the shells to be located precisely.

- The review of our experimental results together with the scientific goals presented above indicates that, with continued development, low-cost missions based upon light weight, thin foil plastic optics with modest angular resolution can provide a significant role in NASA's long term, high energy astrophysics program.

These conclusions summarize the work in progress carried out within the very limited SAO pilot program. What remains to be done, by understanding our results, is to refine the design, manufacturing and test programs to accommodate the development of double reflection, high energy, X-ray telescope optics.

ACKNOWLEDGMENTS

The authors would like to thank Frank C. DeFreze for his help in assembling the X-Ray optics and building the X-Ray test facility, Lawrence K. Knowles and the Harvard Observatory Model Shop staff for their skill in manufacturing the precision parts for the X-Ray optics, Gerald K. Austin for his generous advice during the design of the mechanical structures for the optics and Roberto Candia and Salvatore Varisco for their operational support in Palermo. This research has been supported, in part by NASA SR&T Grant NAG5-5268 and by institutional funding from the Smithsonian Astrophysical Observatory and the Osservatorio Astronomico di Palermo Giuseppe S. Vaiana. The SAO multilayer facility receives support from NASA SR&T Grant NAG5-5095. This work made use of the MRSEC Shared Experimental Facilities at MIT supported by the National Science Foundation under award number DMR94-00334.

REFERENCES

1. NASA NP - 1999 - 11 - 184 - GSFC
2. Schnopper, H. W., Silver, E., Ingram, R., Christensen, F. E., Hussain, A., Barbera, M., Romaine, S., Collura, A., Kentner, A., Bandler, S. and Murray, S., "X-ray optics made from thin plastic foils", *Proc. SPIE,* **3766,** 350 - 361 1999.
3. Schnopper, H. W., "Bragg reflection concentrators for hard X-ray astronomy", *Appl. Opt.,***20**, 1089 -, 1981.
4. Christensen, F. E., Hornstrup, A., Westergaard, N. J., Schnopper, H. W., Wood, J. and Parker, J., "A graded d-spacing multilayer telescope for high energy X-ray astronomy", *Proc. SPIE,* **1546**, 160 -, 1991.
5. Schnopper, H. W., Silver, E., Murray, S., Romaine, S., Bandler, S., Jones, C., Forman, W., Madden, N., Beeman, J., Haller, E., Christensen, F., Westergaard, N., Fabregat, J., Reglero, V,. Gimenez, A., Brosch, N., Liebowitz, E. , Netzer, H., M.Barbera, Collura, A. and Sciortino, S., "*XRASE*: The X-ray Spectroscopic Explorer", *Astron. & Astrophys,* 2001., in press.
6. Silver, E,. Bandler, S., Schnopper, H., Murray, S., Barbera, M., Madden, N., Landis, D., Beeman, J. and E. Haller, "NTD germanium-based microcalorimeters for hard X-ray spectroscopy", *Proc. SPIE*, **4140**, 397- ,2000.
7. Schnopper, H., Silver, E., Murray, S., Jones, C,. Forman, W., Bandler, S., Romaine, S., Slane, P., Grindlay, J, Madden, N. Beeman, J., Haller, E., Smith, D., Barbera, M., Collura, A., Christensen, F., Ramsey, B., Woosley, S,. Diehl, R., Tucker, G., Fabregat, J., Reglero, V. and Gimenez A., "*B-MINE*: Balloon-borne Microcalorimeter Nuclear Line Explorer", *P.A.S.P.*, 2001, in press.
8. Soong, Y. "Conical thin foil X-ray mirror via surface replication", *Proc. SPIE,* **2515**, 94 -96, 1995.
9. Craig, W. C., Christensen, F. E., Decker, T., Hailey, C. J., Harrison, F. A., Hill, R. M., Jimenez-Garate, M., Mao, P. and Schindler, S.," Hard X-ray optics for the HEFT balloon borne payload: Prototype design and status", *Proc. SPIE,* **3445**, 112 - 120, 1999.
10. Romaine, S., Everett, J. Bruni, R., Ivan, A. and Gorenstein, P., "Characterization and Multilayer Coating of Cylindrical X-ray Optics for X-ray Astronomy", *Proc. SPIE,* **3444,** 552 - 555, 1998.
11. Barbera, M. and Collura, A., "X-ray Astronomy Calibration and Testing Facility (XACT)", *P.A.S.P*, **2001**, in press.
12. Clark, A., Bruni, R. J., Romaine, S. E., Schwartz, D. A., Van Speybroeck, L., Yip, P. W., Drehman, A. J. and Shapiro, A. P., "Correlation between X-ray reflectivity measurements and surface roughness", *Proc. SPIE,* **2805**, 268-276, 1996,.
13. Ivan, A.,Bruni, R., Byun, K., Gorenstein, P. and Romaine, S., "Optimization of the broadband reflectance of graded multilayers for hard X-ray mirrors", *Proc. MRS*, 2000, in press.
14. Christensen, F. E., Westergaard, N. J. and Schnopper, H. W., "Measurements of surface scattering of X-rays using a triple axis X-ray spectrometer", *Proc. ESA Workshop on a Cosmic X-ray Spectroscopy Mission*, June 1985.
15. Church, E. L., "Role of surface topography in X-ray scattering, Space Optics Imaging X-ray Optics Workshop", *Proc. SPIE*, **184**, 196 - 202, 1979.
16. Aschenbach, B., "X-ray telescopes", *Rep. Prog. Phys.*, **48**, 579 -629, 1985.