

# Development of Thermally Formed Glass Optics for Astronomical Hard X-ray Telescopes

**William W. Craig, Charles J. Hailey, Mario Jimenez-Garate, and David L. Windt**

*Columbia Astrophysics Laboratory, Columbia University, 550 W. 120<sup>th</sup> Street, New York, NY 10027  
bill@astro.columbia.edu, chuckh@astro.columbia.edu, mario@astro.columbia.edu, windt@astro.columbia.edu*

**Fiona A. Harrison and Peter H. Mao**

*Space Radiation Laboratory, California Institute of Technology, MC 220-47, Pasadena, CA 91125  
fiona@srl.caltech.edu, peterm@srl.caltech.edu*

**Finn E. Christensen and Ahsen M. Hussain**

*Danish Space Research Institute, 30 Juliane Maries Vej, Copenhagen, DK-2100  
finn@dsri.dk*

**Abstract:** The next major observational advance in hard X-ray/soft gamma-ray astrophysics will come with the implementation of telescopes capable of focusing 10-200 keV radiation. Focusing allows high signal-to-noise imaging and spectroscopic observations of many sources in this band for the first time. The recent development of depth-graded multilayer coatings has made the design of telescopes for this bandpass practical, however the ability to manufacture inexpensive substrates with appropriate surface quality and figure to achieve sub-arcminute performance has remained an elusive goal. In this paper, we report on new, thermally-formed glass micro-sheet optics capable of meeting the requirements of the next-generation of astronomical hard X-ray telescopes.

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## 1. Introduction

Sensitive observations of astrophysical sources in the hard X-ray/soft gamma-ray band provide a unique window on physical processes not observable at lower X-ray energies ( $E < 10$  keV). For example, measurements of the high-energy continuum in active galactic nuclei (AGN) are crucial both for interpreting low-energy ( $E < 10$  keV) spectral features, and for constraining the source viewing angle. Cyclotron resonance scattering features, produced near the surfaces of highly magnetized neutron stars, also appear in this energy range. Measurements of the line profiles can be used to infer the magnetic field strength, spatial distribution, geometry of the accretion flow, and the plasma optical depth and temperature.

Extending sensitivity to  $\sim 200$  keV is particularly interesting, as several key nuclear transitions from radioactive elements produced in supernova explosions lie between 50 and 200 keV. Of particular interest are the decays from  $^{44}\text{Ti}$  (68 and 78 keV) and  $^{56}\text{Ni}$  (158 keV).  $^{44}\text{Ti}$  is synthesized near the mass cut (the boundary between the innermost ejecta and the material that falls back to form the collapsed remnant). Since its production and ejection are sensitive to the explosion mechanism as well as the ejecta dynamics, mapping its density and velocity distribution in young supernova remnants provide constraints on these. Probing interesting scales, however, requires sub-arcminute angular resolution and sub-keV energy resolution.  $^{56}\text{Ni}$  is the dominant nuclear product in Type Ia events and the  $^{56}\text{Ni}$  decay time is comparable to the timescale for the ejecta to undergo a transition from optically thin to optically thick (10-30 days). As a result the time evolution of the  $^{56}\text{Ni}$  line flux is especially sensitive to the structure and dynamics of the ejecta as well as to the nuclear abundances and explosion mechanisms. The  $^{56}\text{Ni}$  lightcurve therefore provides a means of differentiating between different models of the supernova explosion.

Achieving the sensitivity to make these measurements requires imaging instruments more than an order of magnitude more sensitive than the current-generation of hard X-ray telescopes. Such large sensitivity gains can only be achieved practically with focusing or concentrating systems, which greatly reduce instrumental backgrounds compared to indirect modulation schemes (e.g. simple collimators, coded aperture telescopes or rotation modulation collimators). Focusing systems have, however, been limited to photon energies below  $\sim 10$  keV because, for metal surfaces, incidence angles for which significant reflectance can be achieved decrease roughly inversely with energy. To extend traditional systems to high energy therefore requires very shallow incidence angles, with many reflectors and long focal lengths.

The recent development of depth-graded multilayer coatings for the hard X-ray band has made designing grazing-incidence systems extending to  $E \geq 100$  keV practical [1,2]. These coatings, which operate on the principal of Bragg reflection, increase, for fixed energy, the incidence angle for which significant reflectance can be achieved [3]. Even with depth-graded multilayer coatings, however, for 10 – 15 meter focal lengths, these systems have relatively small incidence (or graze) angles, and require many shells (typically 70 – 100) per mirror to achieve significant collecting area.

Given this, realizing these designs in practice requires not only the ability to fabricate the multilayer coatings, but the development of optics with appropriate surface quality and figure capable of being manufactured in large quantities at reasonable cost. The deposition technology for fabricating the depth-graded multilayer coatings (at least for the  $E < 100$  keV band) is now relatively mature [4,5]. In this paper, we describe the first demonstration of recently developed, thermally formed glass micro-sheet X-ray optics. These optics, coated with depth-graded multilayers, have demonstrated good imaging performance and excellent

reflectance from X-ray energies of 8 – 170 keV. With the ability to manufacture the substrates inexpensively, this demonstrates for the first time the practicality of sub-arcminute hard X-ray optics of the quality required by next-generation balloon and space missions.

## 2. Technical approach

The glass that forms the basis for the optics we describe here is a form of thin glass sheet developed for use as a substrate for flat panel displays. This glass is available in large (440 x 360mm) sheets as thin as 0.05mm and is relatively flat and uniform. Desag AF45 and D263 borosilicate glasses were used in the measurements presented here. These glasses are produced by process known as ‘overflow’ that produces glass of excellent quality by eliminating mechanical contact with the glass surface during manufacturing. The most relevant characteristic of the glass for our work is an intrinsic smoothness on length scales shorter than about 25 mm. This smoothness is measured by illuminating a 25mm section of the glass with a highly collimated 8 keV X-ray beam. A triple-axis diffractometer utilizes perfect Si(220) channel-cut monochromator and analyzer crystals in a non-dispersive geometry. The setup [6] allows for detection of true scattering from roughness as small as a few Å on length scales up to 2 mm as well as detection of figure errors on the arcsecond level over the illuminated footprint. Integrating the flux as a function of angle produces a profile such as that shown in Figure 1. A typical sample of the AF45 or D263 glass, illuminated over a 25 mm segment by an X-ray pencil beam, contains half of the reflected power within a diameter (the half power diameter, or HPD) of 10 arcseconds. This HPD, comparable to that of a polished mirror, is the key to producing the large geometric area needed to manufacture hard X-ray optics. The glass can be used as an X-ray optic without processing (i.e. polishing or replication) if the overall figure of the optic can be controlled on length scales of 25 mm and greater.

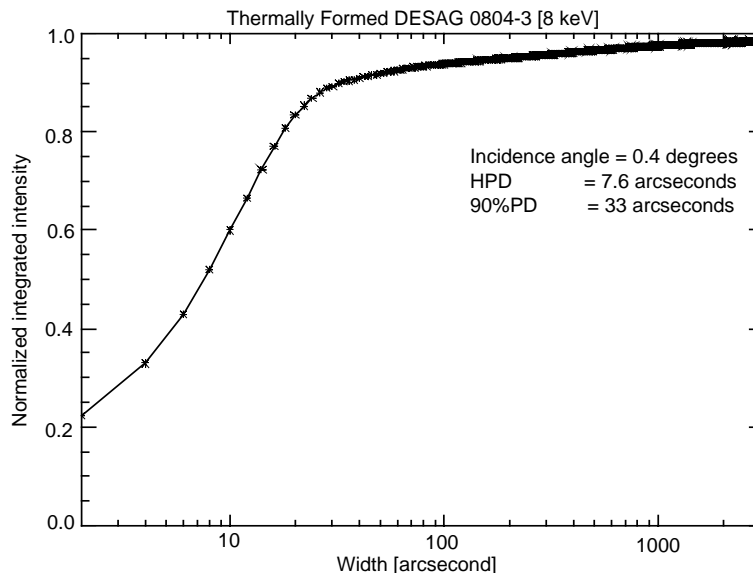


Figure 1: Encircled power diameters from a sample of thermally formed AF45 glass illuminated by a monochromatic X-ray beam with a footprint of 25 x 2mm.

The typical design choice for these optics is a conical approximation to a Wolter-I geometry. This configuration, which employs 2 conical reflectors rather than a hyperboloid and paraboloid is appropriate for missions such as the *Constellation-X* Hard X-ray Telescope

(HXT) [1] or the High Energy Focusing Telescope (HEFT) [2] as the broadening introduced by the approximation ( $\sim 10$  arcseconds) is a negligible error term for the long focal lengths employed. Individual glass pieces are thermally formed into a half cylinder of quartz. The temperature is raised in a controlled manner to approximately 60 degrees C above the annealing point of the glass ( $\sim 620$  °C for D263,  $\sim 705$  °C for AF45), gravity causes the glass to slump into the cylinder. The temperature is then lowered and the glass, which assumes a near cylindrical shape with a radius within a few millimeters of that desired (in the azimuthal direction the glass approximates a catenary), is characterized for large-scale figure using a scanning apparatus that uses the position of a reflected laser beam to measure figure to  $\sim 5$  arcseconds [7]. This characterization typically reveals slight bows, of amplitude  $< \sim 0.1$  mm over the length scale of the piece (200 mm) but negligible errors over shorter length scales.

After thermal forming the glass pieces are trimmed to size azimuthally, (currently into sextants, i.e. 60 degree segments) of length 200 mm, and then coated with the multilayer films appropriate [8] for the shell being built before mounting. The mounting method shown schematically in Figure 2 accommodates small figure errors and constrains the glass piece to the proper conical profile by constraining the sextant to graphite spacers that run along the optical axis. The base of each optics module is a spindle on which the spacers are epoxied. A tooling ball at each end of the central spindle provides the interface point to the optical bench. Each spacer is machined to a precision of  $\pm 2.5 \mu\text{m}$ . Glass pieces, 12 per complete two-bounce shell, are then constrained to the spacers and epoxied into place. After epoxy cure, the next layer of spacers and glass is added and the entire procedure repeated until the telescope module is complete (the HEFT design employs 72 shells or 864 individual pieces of glass per optics module; 14 modules make up the HEFT telescope).

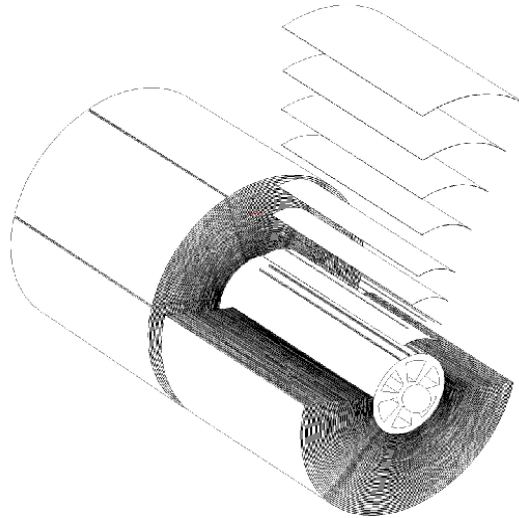


Figure 2: The mounting geometry for the HEFT telescope modules. 72 shells are built up by constraining individual thermally formed glass pieces to precisely machined graphite spacers.

### 3. X-ray measurements

To test the performance of optics constructed using this method, we have constructed a number of prototypes, from simple cylindrical optics through complete double bounce Wolter-I approximations. For simplicity, we typically perform full characterizations of figure and optics performance on single-bounce prototypes. The performance of two-bounce prototypes is also periodically measured. The measurements presented here were performed on a single-bounce prototype optic consisting of 5 multilayer coated shells; close spacing between the first shell and the prototype spindle obscured some of the X-ray flux, only data from the outer 4 shells are considered.

During assembly of the optics, mechanical metrology (e.g. the tolerances on the spacer machining as well as the conformance of the glass to the spacers) is used to monitor performance of the assembly procedure. This metrology was used as input to a raytrace which predicted ~35 arcsecond angular resolution for the assembled one-bounce optic. The optics were then tested with hard X-rays to validate end-to-end performance.

The X-ray testing we present here was performed at the Danish Space Research Institute (DSRI) at 8keV and the European Synchrotron Radiation Facility (ESRF) at energies up to 170 keV. At the DSRI facility, 8keV X-rays from a rotating anode source are directed through a crystal monochromator and a set of slits to produce a low divergence monochromatic X-ray beam. For these measurements a slit width of approximately 0.3mm was used along the optical axis providing an angular resolution of 35 arcseconds FWHM. The beam footprint is ~2mm in azimuth along the cylindrical sample. The reflected X-rays are detected with a one dimensional position sensitive proportional counter located a distance of 2.3m from the optic. The optic is held in a fixture that allows for remotely controlled translation and rotation during testing. After initial alignment the optic is rotated about an axis perpendicular to the optical axis to an incident angle (0.15 degrees typical) where the X-ray pencil beam illuminates the majority of the optic. Final alignment consists of translating the optic so that the beam footprint is centered for a nominal position on the outer shell. The angular distribution of the reflected X-rays is then recorded and after all 5 mirrors are measured the optic is rotated by 2 degrees and the measurement repeated. The test setup samples over 50% of the optical surface.

The figure of the optics was sampled at energies ranging from 18 keV through 170 keV using both the X-ray Optics (BM 5) and High-Energy (ID 15) beam lines at ESRF. At BM5, a detuned double reflection Si(111) monochromator in reflection geometry selected energies of 18, 28 and 34 keV. A Si(333) reflection, together with an absorber (to eliminate the 111 reflection) was used to select 54 and 68 keV energies. At beamline ID15A a double reflection Si(311) monochromator in Laue geometry was used to select energies of 65, 80, 90, 100, 115, 158 and 170 keV.

A CCD camera, optically coupled to an X-ray scintillator array, provides two-dimensional imaging. The camera, located at a distance of 2.6m from the optic, provides an angular resolution of 35 arcseconds FWHM.

Table 1: The half power diameter of the individual shells in arcseconds. Errors, including systematics are estimated to be  $\pm 2''$ .

Shell Number	8 keV	28 keV	68 keV
Shell 2	31	29	-
Shell 3	35	36	33
Shell 4	33	31	-
Shell 5	33	34	-

A histogram showing the distribution of individual pencil beam measurements (with probe beam profile deconvolved) for all shells at 28 keV is presented in Figure 3. The

angular resolution of the probe beams is responsible for the cutoff at ~10-15 arcseconds, a substantial fraction of the individual pencil beam measurements are resolution limited.

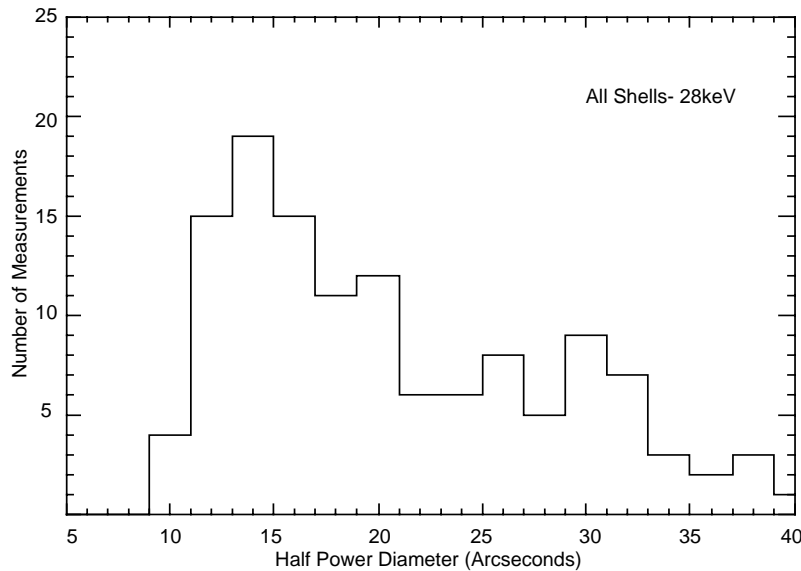


Figure 3: The distribution of individual half power diameter measurements for all shells at 28 keV.

The data from each of these individual measurements, including intensity and detailed X-ray spatial profile, can be added to produce a radially averaged point spread function. For segmented optics, this approach best represents the performance of the final optic. Systematic errors in the alignment and in the fixture that rotates the optic shift the position of the X-ray spot and require that the raw data be corrected before the individual pencil beam measurements are combined. After this correction, and deconvolving by the probe beam PSF, the data are combined to produce the radially averaged point spread function; results are shown in Table 1. Errors in the HPD determination, including statistical and residual systematics, are estimated to be  $\pm 2$  arcseconds. Summing the images along the out-of-plane direction, where the probe beam width is only 2mm, produces a total profile. The combined data for 28 keV is shown in Figure 4.

The data from both 8, 28 and 68 keV give nearly identical values for the half power diameter,  $\sim 35$  arcseconds. At 170keV only a portion of the optic was sampled, however profiles are consistent with a  $\sim 35$  arcsecond half power diameter. The HPD for a 2-bounce optic can be determined, for uncorrelated errors, by multiplying the 1-bounce numbers by  $2^{1/2}$  (see Jimenez-Garate *et al* [7] for a discussion of error terms in these type of optics). Our continuing series of measurements of 2-bounce optical performance for glass optics confirm that this factor is appropriate for optics constructed in the fashion we describe here.

The reflectivity of the optics, typically above 70% throughout the 20-70 keV range the coatings were designed for, is consistent with expectations based on characterization of the W/Si multilayer coatings [5,9].

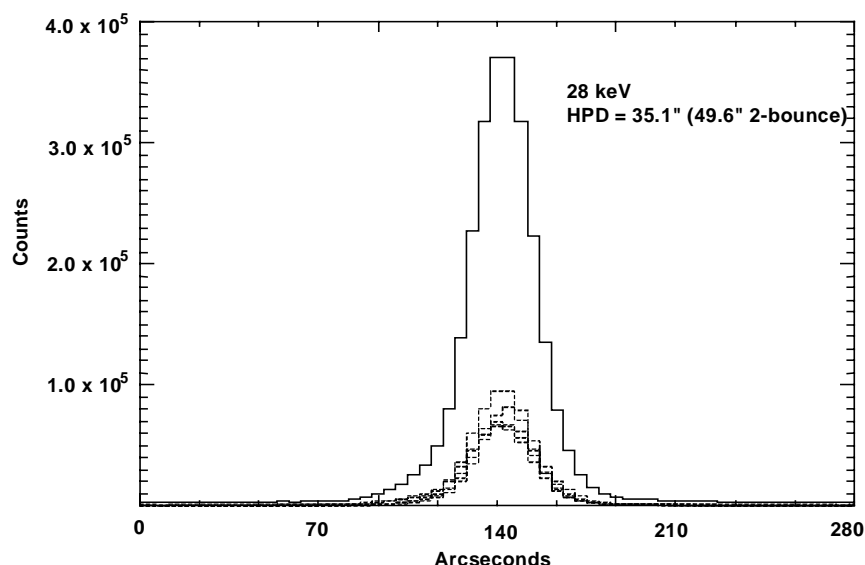


Figure 4: The radially averaged point spread function (PSF) for the shells in the prototype. The solid line is the sum, the individual shell contributions are also shown.

#### 4. Discussion

Thermally formed glass optics are an attractive approach for constructing the large area, high angular resolution optics required by the science. Glass is available in large thin sheets and has a low density ( $2.7 \text{ g/cm}^3$ ), making lightweight, high efficiency optics realizable. The glass we have chosen also has good intrinsic smoothness, is an ideal substrate for deposition of multilayer films, and can be simply and inexpensively manufactured into an X-ray optic, making large geometric areas practical. The results we present here on the performance of mounted, multilayer-coated glass establish that this type of optic is a viable approach to meet the science requirements we describe earlier.

For HEFT and the *Constellation-X* HXT, the sub-arcminute performance we have now achieved already meets all scientific requirements. A high sensitivity hard X-ray imaging mission which could operate up to 200 keV, and for which angular resolution of  $\sim 30''$  is desired, is also realizable using the thermally formed glass technology. The individual pencil beam measurements (Figure 3) indicate that the glass itself is not yet the limiting factor in overall performance. The largest error term in the optic is large-scale figure errors in the constrained glass segments that cause small amplitude systematic variations in the angle within individual sextants. Finite element analysis predicts that changing the position and number of spacers can reduce the magnitude of this error. Small changes in the mounting configuration will be employed in HEFT flight model construction.

Improved angular resolution, below  $20\text{--}30''$ , for hard X-ray telescopes is not required by the science at this point. There are applications, however, where improved resolution would be scientifically useful (*e.g.* *Constellation-X* Spectroscopy X-ray Telescope or other missions with  $5\text{--}10''$  angular resolution requirements). Improvement beyond the  $20''$  level may require improvement in the glass material or thermal forming procedure. A program to investigate the ultimate performance limits has recently begun to explore both of these avenues.

## 5. Conclusion

We have demonstrated performance from optics constructed using a method that is easily scalable and capable of producing the large area, high performance optics needed for a new generation of hard X-ray imaging telescopes. The good figure, ~35" HPD, low scattering and excellent reflectivity of these optics, along with the promise of significant improvement in their ultimate performance make these optics a practical approach for construction of the large area telescopes for next generation observatories.

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