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ORIGINAL ARTICLE

Development of the *HEFT* and *NuSTAR* focusing telescopes

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Abstract Hard X-ray/soft gamma-ray astrophysics is on the verge of a major advance with the practical realization of technologies capable of efficiently focusing X-rays above 10 keV. Hard X-ray focusing telescopes can achieve orders of magnitude improvements in sensitivity compared to the instruments based on coded apertures and collimated detectors that have traditionally been employed in this energy band. Compact focal planes enable high-performance detectors with good spectral resolution to be employed in efficient, low-background configurations. We have developed multilayer coated grazing incidence optics and solid state Cadmium Zinc Telluride focal plane systems for the *High Energy Focusing Telescope (HEFT)* balloon-borne experiment, and for the *Nuclear Spectroscopic Telescope Array (NuSTAR)* Small Explorer satellite. In this paper we describe the technologies, telescope designs, and performance of both experiments.

Keywords X-ray telescopes · X-ray optics · X-ray detectors

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1 Introduction

The last decade has seen a major technological advance in hard X-ray/soft gamma-ray astronomy – the ability to focus efficiently – creating the potential for instruments that improve spatial and spectral resolution by more than two orders of magnitude at energies above 10 keV. Extending grazing incidence telescopes to operate efficiently in the hard X-ray band requires shallow graze-angle optics and position sensitive detectors with high quantum efficiency from 10–100 keV. Incorporating these technologies into astrophysical instruments results in greatly enhanced signal to background ratios compared to coded aperture imagers.

Several research groups have developed focusing hard X-ray systems over the last ten years, and three balloon experiments have been constructed incorporating them. The *InFOCuS* experiment [4] extends the segmented aluminum foil mirror technology developed for *Astro-E2* to 40 keV utilizing an optic coated with Pt/C depth graded multilayers. The *InFOCuS* focal plane consists of a CdZnTe detector with a 12 × 12 array of 2-mm pixels. The telescope achieves angular resolution of $2.2'$ (HPD) and spectral resolution of 4 keV at 32 keV, and has flown twice, in 2001 and 2004. The *HERO* experiment [5] uses shallow graze-angle iridium-coated replicated nickel optics and xenon gas scintillation proportional counters to achieve $45''$ (HPD) angular resolution and 1.5 keV (FWHM) energy resultion at 30 keV. *HERO* flew in 2001 with a small complement of shells, and in Spring 2005 with three telescope modules.

In this paper, we describe the *High Energy Focusing Telescope (HEFT)* balloon payload, as well as the *Nuclear Spectroscopic Telescope Array (NuSTAR)* Small Explorer mission. Both of these experiments are based on multilayer-coated formed glass segmented optics and CdZnTe pixel detectors. *HEFT* flew once in Spring 2005 with a complement of three telescopes, demonstrating angular resolution of $1.5'$ (HPD) and with spectral resolution of 1 keV (FWHM) at 60 keV. Results from the flight are being published elsewhere. *NuSTAR* employs demonstrated improvements to the optics to achieve $40''$ (HPD) angular resolution in a high throughput three-module telescope array. In this paper we describe the optics and detector technologies, and the *HEFT* and *NuSTAR* experiment designs and performance.

2 Depth graded multilayer optics

For *HEFT* and *NuSTAR* we developed depth-graded multilayer coated mirrors in a conical approximation to the Wolter I geometry. The optics are based on formed glass; each shell (full figure of revolution) is assembled from multiple segments [3]. Each segment is thermally formed from a glass sheet, and is coated using a planar magnetron sputtering system developed at the Danish National Space Centre for these programs [2]. The mirrors are assembled layer by layer using graphite spacers epoxied to the glass then machined to accomodate the next layer [1]. Figure 1 shows the assembled *HEFT* flight optics.

The angular resolution achieved using this method is currently dictated by the substrate quality, and depends on the segment size as well as the degree to which substrates are preselected based on figure. The *HEFT* optics achieved $1.5'$ HPD with no selection and 20 segments per shell. Several prototype optics have demonstrated that we can achieve $40''$ HPD with 32 segments/shell and 50% preselection on glass segments.

Fig. 1 Photo of the three *HEFT* flight optics. Each unit is fabricated from formed, multilayer-coated glass

Fig. 2 Photo showing a *HEFT* focal plane detector system. Two CdZnTe/ASIC hybrid pixel sensors are mounted side-by-side

3 Cadmium zinc telluride pixel detectors

We employ CdZnTe pixel detectors for the *HEFT* and *NuSTAR* focal planes. A focal plane is comprised of two hybrid sensors (see Figure 2). An individual sensor consists of a $1.2 \times 2.4\times$ cm, 2 mm thick CdZnTe crystal, with the anode contact segmented into pixels with 500 μm pitch. Gold stud/epoxy interconnects couple the sensor pixel contacts to a custom low-noise readout chip. The ASIC, designed at Caltech for *HEFT*, contains one circuit for each pixel, laid out on a grid exactly matching the detector pixel array.

The state of the art design achieves excellent imaging and spectral performance, as well as the ability to measure the interaction depth of the event in the detector. Figure 3 shows an ^{241}Am spectrum from 100 pixels summed together (somewhat larger than, but not atypical of the number to be included in a point source reconstruction) taken at -5°C. The spectrum includes all detected X-ray events, including those where charge is shared among multiple

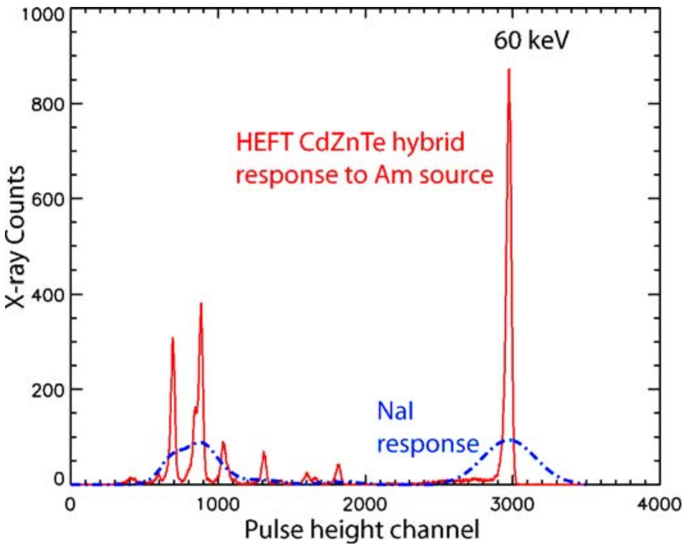


Fig. 3 Spectrum of an 241Am source illuminating 100 pixels of the *HEFT* detector. All events, including those where charge is split among multiple pixels, are included. For comparison, the blue line shows the same spectrum convolved through the response of an NaI detector

pixels. The FWHM of the 60 keV line is 900 eV, and of the 14 keV line is 800 eV (FWHM). The depth sensing ability, enabled by the ASIC design, allows events occuring in the back portion of the detector to be rejected as background, resulting in a factor 2–3 additional background rejection.

4 *HEFT* design and performance

HEFT is a balloon payload developed by a collaboration among Caltech, Columbia, the Danish National Space Center (DNSC), Lawrence Livermore National Laboratories (LLNL) and Stanford University. Figure 4 shows a photo of the *HEFT* payload, indicating the major components. The telescope contains three co-aligned conical-approximation Wolter I mirror assemblies, each of which focuses hard X-rays/soft gamma-rays onto a shielded, solid-state Cadmium Zinc Telluride (CdZnTe) focal plane. The focal plane modules are housed inside a kevlar pressure vessel. The instrument focal length is 6 m.

Table 1 provides an overview of the performance characteristics and instrument parameters. Each of the three optics has 70 shells, with shell radii ranging from 4–12 cm. The reflectors are coated with W/Si multilayers, which provide good reflectance up to the W K-edge at 69.5 keV. The lower energy limit is determined by atmospheric attenuation at balloon altitudes. The total instrument collecting area on-axis is $100\,\mathrm{cm}^2$ at 30 keV, not accounting for atmospheric attenuation. Each detector is surrounded by a Pb/Sn/Cu graded $-$Z passive well housed inside a 2-cm thick plastic scintillator. This arrangement attenuates cosmic and atmospheric backgrounds, and vetos charged particles that create local background in the passive shield. While not as effective as an alkali halide shield (NaI or CsI), this configuration provides a cost-effective approach to reducing detector background.

Table 1 Instrument performance characteristics and configuration. Sensitivity is listed for 3σ threshold, 20 ksec integration (corresponding to two source transits)

Instrument performance characteristics		Instrument parameters	
Energy range	20–70 keV	Num. modules	3
Angular resolution (HPD)	$1.5'$	Focal Length	6 m
FOV (20 keV)	$17'$	Optics	Conical Wolter-I
Sensitivity (mCrab)	2 (20 - 60 keV)	Mirror substrates	Formed glass
Line sensitivity (γ/cm^2/s)	2×10^{-5} (68 keV)	Multilayer	W/Si
Energy Resolution (fwhm)	980 eV (68 keV)	Detector	2 mm thick CdZnTe
Effective area (3.5 g/cm^{-2})	50 cm^2 (40 keV)	Shielding	Graded-Z/plastic
Aspect reconstruction (rms)	$6''$	Envelope	6.5 m × 1.25 m diam.
Pointing stability (rms)	$30''$	Weight	1854 kg
Time resolution	1 m sec	Power	400 Watts

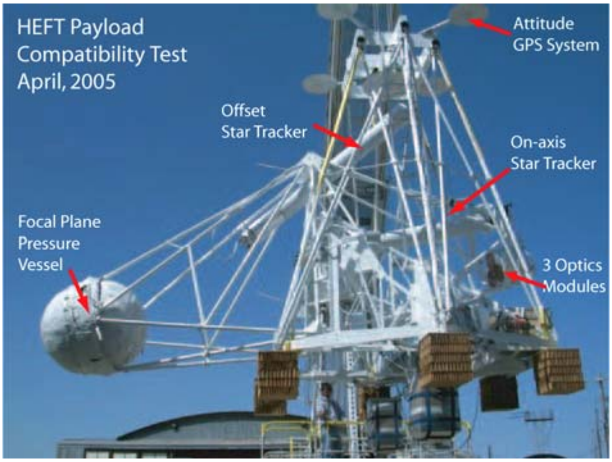


Fig. 4 Photograph of the *HEFT* payload indicating the major components of the experiment

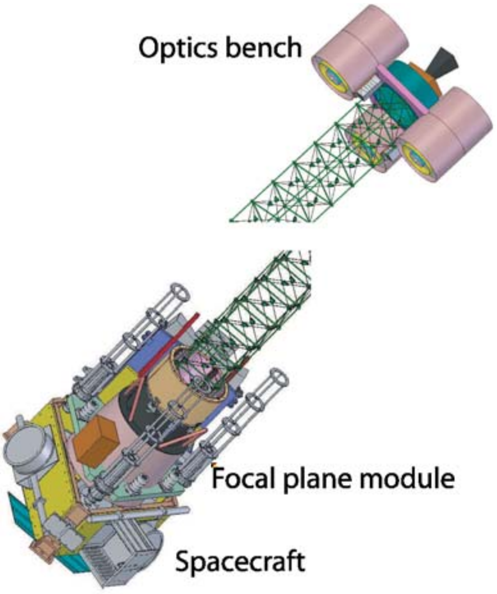
HEFT was launched on May 18, 2005 from Ft. Sumner, NM. During this flight we used observations of three bright point sources; the Crab, Cygnus X-1, and GRS +1915 to verify the instrument pointing stability, imaging, and throughput. Results from this flight are being published elsewhere.

5 *NuSTAR* design

The *NuSTAR* Small Explorer satellite is based on the technologies developed for the *HEFT* experiment, combined with an extendible optical bench developed by ABLE Engineering and the Jet Propulsion Laboratory for the Shuttle Radar Topography Mission. *NuSTAR* was selected for a Phase A study in November, 2003 as one of four missions to compete for two launch opportunities. In January 2005 *NuSTAR* was selected for a launch date of February 2009, and was placed into an extended technical development phase.

NuSTAR consists of three co-aligned telescope modules with a 10-m focal length. The optics and detectors are placed at either end of an extendible mast. For launch the mast is stowed inside a canister, and the entire payload fits inside a Pegasus XL shroud. *NuSTAR*

Fig. 5 The *NuSTAR* payload, with each end shown separately



will be placed into an Equatorial circular 550 km orbit. Figure 5 shows a view of the two ends of the *NuSTAR* payload after deployment. The bench housing the three optics modules is extended outward from the spacecraft end, which houses the three focal plane modules.

The optics consist of 130 shells each, with radii ranging from 5.5 to 16.9 cm. The shells are coated with a combination of W/SiC and Pt/SiC multilayers, with the coating dependent on the shell graze angle. This, combined with the relatively low graze angles, provides reflectance with a smooth response extending to 80 keV. *NuSTAR* will utilize smaller glass segments (32 per shell) compared to *HEFT*, and in addition the substrates will be preselected for figure quality. We have demonstrated through several prototypes that by accepting the best 50% of the glass segments, *NuSTAR* will achieve angular resolution (HPD) of $40''$.

The *NuSTAR* focal plane detectors have the same dimensions as the *HEFT* focal planes, but they are surrounded by an active CsI shield rather than the graded-Z/plastic shield used on *HEFT*. This, combined with the depth-sensing capability of the detectors, reduces the internal detector background to very low levels ($<10^{-4}$ cts cm^{-1}, s^{-1} from 10–80 keV). In addition to the active well-shaped shield, an aperture stop consisting of rings of graded-Z material reduces diffuse cosmic background. The aperture stop deploys simultaneously with the mast after launch.

6 *NuSTAR* performance

Table 2 summarizes the *NuSTAR* performance. Compared to coded aperture instruments that have operated in the same band, *NuSTAR* achieves more than two orders of magnitude improvement in continuum flux sensitivity. The excellent energy resolution of the detectors will allow measurement of velocity shifts in the ^{44}Ti lines at 68 and 78 keV of ±1000 km s^{-1}.

Using the combination of sensitivity, spectral and spatial resolution, *NuSTAR* will be able to undertake investigations not previously possible in the hard X-ray band. In extragalactic survey fields *NuSTAR* can resolve 50% of the hard X-ray background at 30 keV, and will

Table 2 *NuSTAR* instrument performance.

Energy range	6–80 keV
Angular resolution (HPD)	40″
FOV	$8.4 \times 8.4'$
Source positions	5″
Spectral resolution	900 eV 68 keV
Timing resolution	0.1 ms
Line sensitivity (10^6 s, 68 keV)	10^{-7} ph/cm^2/s
Continuum sensitivity	0.7 μCrab (20 keV)
(10^6 s, 3σ, $\Delta E/E) = 0.5$	6 μCrab (60 keV)
Background in HPD/module (40 keV)	1.1×10^{-5} cts/s/keV
Effective area (20 keV)	500 cm^2
ToO response	<24 h

detect several hundred obscured AGN in its 2 square degree survey fields. *NuSTAR* can also spatially resolve the ^{44}Ti line in Cas A, mapping the line doppler shifts with $1000\,\mathrm{km\,s^{-1}}$ resolution in 40″ spatial bins. In surveys of the Galactic center region, *NuSTAR* can resolve the hard source populations discovered by *Integral* and *XMM*, and study the distribution in latitude of any truly diffuse component.

7 Summary

The *HEFT* balloon experiment has demonstrated hard X-ray focusing optics and solid state pixel detectors by imaging cosmic sources in this band. These observations have fully verified the expected throughput, resolution, and sensitivity of the *HEFT* instrument. *NuSTAR*, which is based on the *HEFT* technologies, is ready to proceed to phase B, and will realize the potential of hard X-ray focusing in space.

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