Development of the High-Energy Focusing Telescope (HEFT) balloon experiment

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ABSTRACT

The *High Energy Focusing Telescope* (HEFT) is a balloon-borne experiment employing focusing optics in the hard X-ray/soft gamma-ray band (20 – 100 keV) for sensitive observations of astrophysical sources. The primary scientific objectives include imaging and spectroscopy of ^{44}Ti emission in young supernova remnants, sensitive hard X-ray observations of obscured Active Galactic Nuclei, and spectroscopic observations of accreting high-magnetic field pulsars. Over the last four years, we have developed grazing-incidence depth-graded multilayer optics and high spectral resolution solid state Cadmium Zinc Telluride pixel detectors in order to assemble a balloon-borne experiment with sensitivity and imaging capability superior to previous satellite missions operating in this band. In this paper, we describe the instrument design, and present recent laboratory demonstrations of the optics and detector technologies.

1. INTRODUCTION

The technical difficulties associated with extending grazing incidence X-ray optics to high energy, coupled with the lack of high-spatial resolution hard X-ray detectors have limited large-area focusing telescopes to the soft X-ray band. The recent development of depth-graded multilayer optics and high-Z solid state pixel detectors, however, now makes true focusing possible at high X-ray energies. This advance will provide dramatic improvements in sensitivity and angular resolution not achievable with the current generation of background-limited collimated and coded-aperture hard X-ray instruments.

The *High-Energy Focusing Telescope (HEFT)* will be among the first experiments to employ focusing optics for astrophysical observations at photon energies above 10 keV. Over the last four years the *HEFT* collaboration has developed high-reflectance depth graded multilayers, low-mass X-ray optics based on new thermally-formed glass substrates, and high spectral resolution Cadmium-Zinc Telluride pixel detectors all optimized for astronomical hard X-ray/soft gamma-ray telescopes. We are currently assembling a large-area balloon payload based on these technologies. The primary scientific objectives for the instrument include imaging and spectroscopy of ^{44}Ti emission in young supernova remnants, sensitive hard X-ray observations of obscured Active Galactic Nuclei, and spectroscopic observations of accreting high-magnetic field pulsars. In the following sections, we describe the *HEFT* telescope design, provide an overview of the individual technologies including results from laboratory demonstrations, and finally we present the projected performance.

2. DESIGN OVERVIEW

The *HEFT* telescope (shown in Fig. 1) consists of an array of co-aligned conical-approximation Wolter I mirror assemblies, each of which focuses hard X-rays/soft gamma-rays (20 – 100 keV) onto an individual, shielded, solid-state Cadmium Zinc Telluride (CdZnTe) pixel detector. Depth-graded multilayer coatings provide high-energy reflectivity

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Instrument Performance Characteristics		Instrument Parameters	
Energy range	20 – 100 keV	Number of modules	14
Angular Resolution (HPD)	$1'$	Focal Length	6 m
FOV (20 keV)	$17'$	Optics	Conical approx. Wolter-I
Sensitivity (γ/cm^2/s/keV) - 3σ	2×10^{-7} @ 40 keV	Mirror substrates	formed glass
Line Sensitivity (γ/cm^2/s) - 3σ	4×10^{-6} @ 68 keV	Multilay er	W/Si & Cu/Si
Energy Resolution (fwhm)	980 eV @ 78 keV	Detector	2 mm thick CdZnTe pixel
Effective Area	250 cm^2 @ 40 keV	shielding	graded-Z/plastic
Aspect Reconstruction (rms)	$6''$	Envelope	6.5 m $\times$ 1.25 m diam.
Pointing Stability (rms)	$20''$	Weight	1270 kg
Time Resolution	1 msec	Power	300 Watts

Table 1. Instrument Performance Characteristics and Configuration

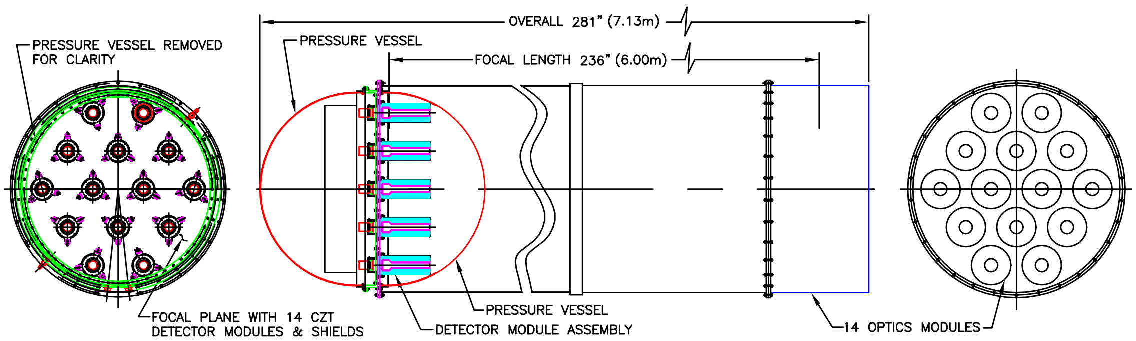

Figure 1. *Schematic drawing of the* HEFT *telescope.*

at reasonable graze angles, with response extending to 100 keV. The thin nested-shell mirrors are separated from the focal plane detectors by 6 meters. Fourteen modules are packed into a 1.25 meter diameter structure, which is mounted on a precision balloon pointing platform. Table 1 provides a summary of the instrument configuration and performance characteristics.

3. MULTILAYER HARD X-RAY OPTICS

Figure 2. *Formed glass mirror shells (300 μm thick) coated with* HEFT *design W/Si multilayers.*

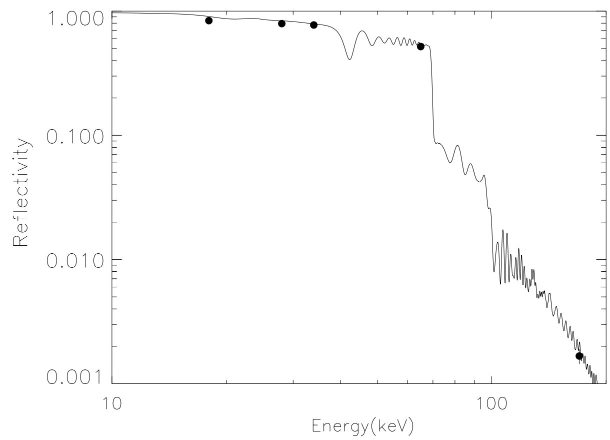

Figure 3. Data and model for reflectance versus energy at a graze angle of 2.2 mrad (the center of the on axis graze angle range for this multilayer design). The error bar is smaller than data point if not shown. The full line is the model calculation assuming an interface width of 4.5Å.

HEFT employs depth-graded multilayer coated mirrors in a conical approximation to the Wolter I geometry. We use segmented mirrors, where the upper and lower sections are assembled from quadrants (as done for *SODART*, *ASCA*, and *Astro-E*).[1] Each of the 8 segments in a shell is coated with a graded multilayer. We selected this approach over replicated integral shells such as those used on *XMM* since, at these energies, even with multilayer coatings the average mirror graze angles are small, requiring many shells/module. The cost of such a large number of mandrels (required for shell replication) is prohibitive. Table 2 provides an overview of the *HEFT* mirror parameters.

Mirror Parameters	
substrate	formed glass
shells/module	72
shell thickness	0.3 mm
length	40 cm
inner radius	4 cm
outer radius	12 cm
max. graze angle	.005 rad
Multilayer Parameters	
Materials	W/Si $\theta > 3.5 mrad$
	Ni/Si ($\theta < 3.5 mrad$)
Max. thickness	3.6μm
# layers (avg.)	800

Table 2. *Mirror Module Baseline Parameters.*

To meet the *HEFT* 1′ HPD requirement in a technology compatible with the cost constraints of a balloon experiment we have developed new, inexpensive glass substrates. The availability of thin glass (developed for flat panel displays) that is smooth and flat on all relevant length scales,[2] makes possible the inexpensive fabrication of conical approximation optic segments formed by thermal slumping of the microsheet into a quartz mandrel (see Craig *et al.* 1998 for details). The glass provides an ideal surface for direct multilayer deposition, without the complicated epoxy replication step required to smooth aluminum foils.[3,4]

To achieve broad-band reflectance extending up to 100 keV, *HEFT* employs depth graded W/Si and Ni/Si multilayer coatings. A multilayer structure is a stack of thin layers of alternating high and low index of refraction materials arranged so that the small reflections from each interface add in phase, giving rise to usable reflectance. In a depth-graded structure, the bilayer thicknesses vary with depth into the film, so that different layers are optimized to reflect different wavelengths, providing broadband response.[5]

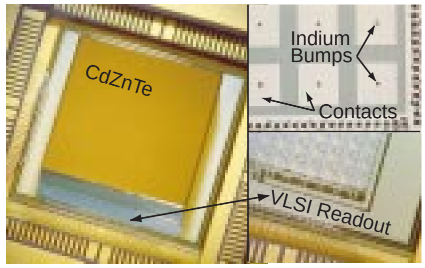

Figure 4. Photo of the *HEFT* prototype, showing detector geometry and packaging. In the final detector array, four CdZnTe will be tiled to fill the focal plane.

Detector Characteristics	
Sensor	CdZnTe
Pixel size	500μm
Thickness	2 mm
Unit dimension	1.3 × 1.3 cm
Units/focal plane	4
Performance	
ΔE/E (FWHM, 70 keV)	1.4%
Elect. noise (rms, leakage incl.)	40 e^-
Power/chan	50 μW
Threshold	1 keV
QE (50 keV)	98%

Table 3. *HEFT* CdZnTe Detector Parameters.

We selected the Si-based multilayer materials Ni/Si and W/Si for their high reflectance and sputter yields. The high reflectance results from the small achievable interface widths (a combination of interdiffusion and interface roughness) of $\sigma_{if} = 3.5 - 4.5$ Å. The Si deposition rate is considerably higher than for C (another common low-Z spacer) providing for efficient mirror production. A detailed description of the multilayer growth and characterization can be found in Windt *et al.* (2000).

The effective area and FOV are very sensitive to the bilayer thickness distribution, the number of bilayers, and the materials used. For *HEFT*, we have developed a systematic optimization procedure that tunes the multilayer parameters as a function of graze angle (θ_g) to maximize bandpass and FOV given constraints imposed by the physical parameters of the multilayer materials. A detailed description of the design and optimization procedure can be found in Mao *et al.* 1999.

We have recently characterized the high-energy (up to 170 keV) performance of a prototype optic at the European Synchrotron Radiation Facility (ESRF). The optic consisted of a stack of five quadrant mirror segments in a single reflection cylindrical geometry. We coated each section with a different multilayer design, optimized for a different graze angle range in the *HEFT* telescope. Detailed results from the reflectance and imaging measurements can be found in Christensen *et al.* (2000) and Craig *et al.* (2000) respectively. Figure 3 summarizes data taken at several different energies at a graze angle of 2.2 mrad, and shows the excellent agreement between the measurements and model calculation assuming an interface width of 4.5 Å for the W/Si multilayer. Analysis of imaging data consistently indicated a figure of $40 - 50''$ (HPD) for two reflections, dominated by large scale deviations from ideal figure. Finite element analysis indicates that we can control these errors by making small changes in the mounting procedure. A new set of prototypes, incorporating these improvements, are now under development, and we expect the *HEFT* mirrors to easily achieve sub-arcminute imaging.

4. CADMIUM ZINC TELLURIDE PIXEL DETECTORS

The principal characteristics of the *HEFT* pixel detector are summarized in Table 3. The sensor consists of a 1.3 cm × 1.3 cm × 2 mm thick CdZnTe crystal, with the back contact segmented into $400 \times 400\mu$m squares placed on 500μm

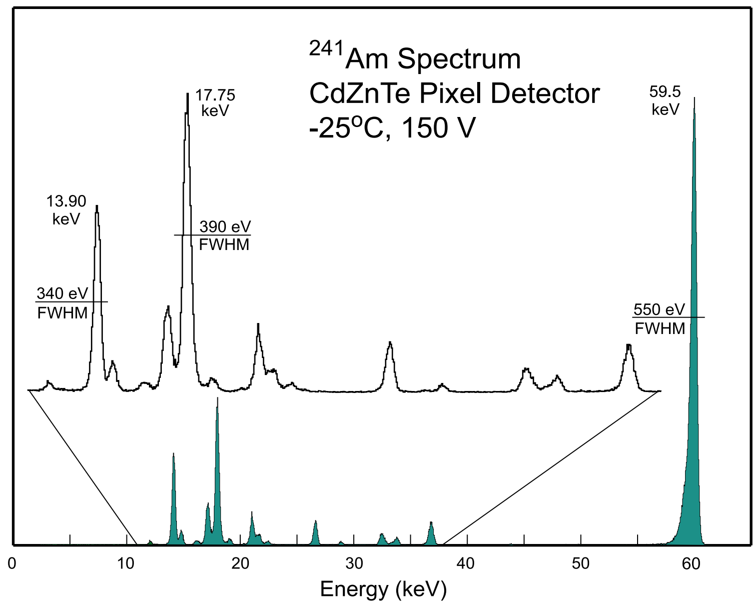

Figure 5. *Measured spectrum of a ^{241}Am source illuminating the center of a pixel of the* HEFT *detector prototype operated at -25°C. The rms electronic noise contribution is 0.35 keV equivalent (70 e$^-$), and the threshold is set at ∼2 keV.*

centers. The sensor is connected via indium bump bonds to a readout chip containing one circuit for each pixel, laid out on a grid exactly matching the detector pixel array (Fig. 4). To fill the focal plane, we tile four detectors in a 2×2 grid. We use multiple, moderate sized detectors due to the prohibitive cost and low yield of large, high quality CdZnTe crystals and VLSI chips. The small (∼200 μm) gap between sensors introduces little dead area, with negligible effect on instrument performance.

To achieve the aggressive energy resolution goal we set for *HEFT* we have developed a custom, low-noise VLSI readout chip, and investigated optimal contact geometries.[10] Details of the readout design can be found in Cook *et al.* (1999). Our recent prototype 8×8 pixel chip with 670μm pixels bonded to a CdZnTe detector has demonstrated FWHM energy resolution of 550 eV at 60 keV when operated at -25°C (Figure 5), and 980 eV when operated at room temperature. We have recently submitted the final 500μm pixel prototype chip for fabrication, and expect to have the final flight chips in house by the end of CY2000.

5. PROJECTED TELESCOPE PERFORMANCE

Using model calculations with parameters derived from the prototype tests, we can confidently predict the projected performance for *HEFT*. The reflectance and resolution of the prototype optics with W/Si multilayers have been well characterized by the measurements described above. For the Ni/Si coatings, we can use laboratory measurements made at lower energy (8 keV) to derive parameters used to extrapolate reflectance to higher energy. In addition, we have a good understanding of the detector resolution and efficiency from laboratory characterizations of the 8×8 pixel hybrid detector. We can accurately calcuate the effective area, and predict the sensitivity to better than a factor of two. The primary uncertainty affecting the sensitivity estimates is the calculation of the in-flight background.

Figures 6 and 7 show these calculations, assuming the multilayer design described in Mao *et al.* (1999), reflectance based on interface widths of $\sigma = 4.5$ Å derived from measurements, and measured detector efficiency. We have included the effect of absorption in the residual atmosphere at 3.5 g/cm^2 expected for the balloon observations. The tremendous sensitivity improvement of focusing experiments over coded-aperture instruments is demonstrated by the comparison to our previous large-area balloon experiments, *GRIP* and *GRATIS*.

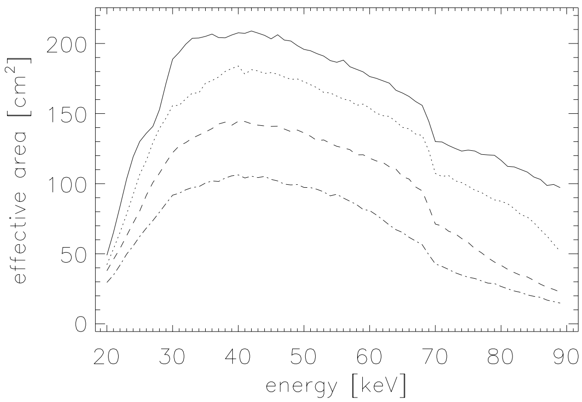

Figure 6. *Raytrace calculations of the experiment effective area on axis, and at 0.5mrad intervals off-axis, including atmospheric attenuation due to 3.5 g/cm*^{2}.

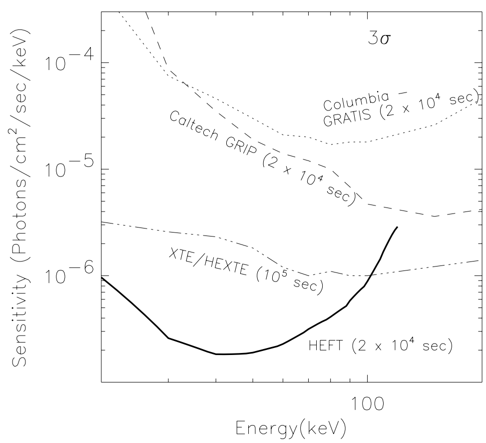

Figure 7. *The sensitivity of* HEFT *for observations from a balloon platform compared to the large-area coded aperture instruments* GRIP *(Caltech) and* GRATIS *(Columbia). The energy bandwidth is* $\Delta E/E = 50\%$*, and we assume an atmospheric column depth of 3.5 g cm*$^{-2}$.

6. CONCLUSION

Major technological advances over the last three years; the development of focusing optics and high spatial and spectral resolution hard X-ray detectors, will bring about dramatic improvements in observational capability in hard X-ray/soft gamma-ray astrophysics. In the next three years, the dramatic improvements in sensitivity and angular resolution over what is currently available with background-limited non-focusing hard X-ray instruments will be realized on balloon platforms. Experiments like *HEFT* will enable entire new classes of hard X-ray observations, such as the detailed study of large samples of extragalactic objects, and the mapping of non-thermal diffuse emission.

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