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FIRST IMAGES FROM HERO, A HARD X-RAY FOCUSING TELESCOPE

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ABSTRACT

We are developing a balloon-borne hard X-ray telescope that utilizes grazing-incidence optics. Termed HERO, for High-Energy Replicated Optics, the instrument will provide unprecedented sensitivity in the hard X-ray region and will achieve millicrab-level sensitivity in a typical 3 hr balloon-flight observation and 50 μcrab sensitivity on ultralong-duration flights. A recent proof-of-concept flight, featuring a small number of mirror shells, captured the first focused hard X-ray images of galactic X-ray sources. Full details of the payload, its expected future performance, and its recent measurements are provided.

Subject headings: balloons — instrumentation: detectors — stars: imaging — telescopes — X-rays: general

1. INTRODUCTION

Grazing-incidence optics have fostered most of the spectacular advances in soft X-ray ($\leq$10 keV) astronomy. Thanks to its superb mirrors, the *Chandra* X-ray observatory, with a collecting area similar to that of the detectors on the first X-ray–astronomy satellite (*Uhuru*), has 5 orders of magnitude more sensitivity. The hard X-ray (>10 keV) band, however, has awaited similar developments and has thus remained *relatively* unexplored. Despite its scientific importance as a region where nonthermal emission begins to dominate, technical difficulties have prevented the development of useful hard X-ray telescopes. This situation is now changing with the construction of several balloon payloads carrying different types of high-energy focusing optics. The HERO (High-Energy Replicated Optics) program, developed at NASA's Marshall Space Flight Center, is the first of these to obtain focused images of astronomical X-ray sources at hard X-ray energies (20–45 keV).

2. APPROACH

The HERO hard X-ray optics are full-shell electroformed-nickel-replicated (ENR) mirrors coated with iridium to enhance high-energy reflectivity. As the critical grazing angle for reflection varies approximately inversely with energy, these mirrors employ smaller angles than their low-energy counterparts and consequently have smaller diameters and collecting areas per shell. Useful total collecting areas are achieved by employing multiple shells and by utilizing large length-to-diameter shell aspect ratios.

The principal attraction of the replication process, which has been used so successfully in Europe for such missions as *XMM-Newton* (Aschenbach et al. 2000), is the superior (geometric) angular resolution afforded by the inherently stable full-shell optics as compared to alternate technologies such as segmented optics. The benefit goes beyond the desirable ability to make more detailed images of extended objects and avoid source confusion in crowded fields. It also has a direct bearing on the sensitivity of the telescope, in that the relevant detector background scales with the area of the focal spot. Thus, for background-limited observations, the sensitivity scales with the mirror half-power diameter (HPD), and therefore, high-resolution optics have a significant advantage over their lower resolution counterparts, particularly for multimodule, long focal length geometries.

One drawback with earlier ENR technology was the low strength of the pure nickel deposit, which necessitated relatively thick and heavy shells. We have refined the process to create a high-strength alloy that permits fabrication of thin, lightweight mirrors (Engelhaupt et al. 2000). For the HERO program, the mirror shells are 0.25 mm thick. However, the process permits even thinner shells ($\leq$0.1 mm) if desired.

3. THE HERO PAYLOAD

The HERO science payload will comprise 16 identical mirror modules, each housing 15 nested shells, mounted on a carbon-fiber optical bench 6 m above an array of focal-plane detectors. The inner mirrors of each module have response to the iridium K edge at 75 keV, whereas the outermost mirrors cut off at 40 keV. The total effective area, neglecting atmospheric absorption, will be 200 cm^2 up to 40 keV and greater than 100 cm^2 at 60 keV. Future plans may include the application of special graded multilayer coatings on larger shells to give enhanced reflectivity at higher energies while taking full advantage of the superior performance of the replicated optics.

Long-duration and ultralong-duration balloon (ULDB) flights[6] provide excellent opportunities to realize the very high sensitivities afforded by even modest collecting areas. Folding in typical background counting rates, we estimate 5 σ sensitivities in a 10 keV wide bandwidth at 40 keV of

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[6] See http://www.wff.nasa.gov/~uldb.

5×10^{-6} photons cm^{-2} s^{-1} keV^{-1} in a single 10^4 s observation at balloon altitudes and 2×10^{-7} photons cm^{-2} s^{-1} keV^{-1} in a 10^6 s observation. This latter sensitivity, 3 orders of magnitude better than achieved in the *HEAO 3* hard X-ray survey, will make available thousands of sources to select from for detailed study.

3.1. *Optics*

The HERO mirrors are conical approximations to a Wolter type 1 geometry, with a monolithic shell structure containing both "parabolic" and "hyperbolic" segments. Each shell is 0.25 mm thick electroformed nickel, coated on the inside with 50 nm of sputtered iridium to enhance high-energy reflectivity (Table 1.) The mirrors' fabrication employs replication techniques in which the shells are electrodeposited onto superpolished electroless-nickel-plated aluminum mandrels from which they are subsequently released by cooling. To keep costs appropriate to a balloon program, the mandrels were coarsely ground to figure (commercially) and transferred to an in-house polishing machine. The resulting mandrels and their subsequent shells were limited in performance by micron-amplitude axial figure errors. Ramsey et al. (2000) give details of measurements on these early optics, where typical HPDs were around 30″. We have since switched to vertical diamond turning, which produces a better mandrel figure accuracy and a higher quality surface that requires less polishing. The quality of these mandrels yields 10″-level HPD geometric cores, consistent with our target of 15″ system-level performance. The 6 m focal length optics replicated from these mandrels are currently being tested.

For a recent demonstration flight, we fabricated special 3 m focal length mirror shells that could be accommodated in our as-yet-unmodified (§ 3.3) gondola. Two sets of three shells were nested in separate modules, the housings of which were made of a carbon-composite tube wound to have the same thermal expansion coefficient as nickel. A stainless-steel spider arrangement held the mirrors concentric at both ends. Measured X-ray performance (Ramsey et al. 2000) showed response up to 50 keV and half-power diameters of 30″, consistent with predictions based on optical-metrology of these early mandrels. The system-level performance, degraded by machining errors in the spiders at each end of the mirror modules and alignment uncertainties, was 45″.

TABLE 1
HERO Final Mirror Configuration

Parameter	Value
Mirror shells per module	15 (3)
Inner shell diameter	50 mm (44 mm)
Outer shell diameter	94 mm (48 mm)
Total shell length	610 mm
Focal length	6 m (3 m)
Type	Conic approximation to Wolter-1
Fabrication process	Electroformed nickel replication
Shell thickness	0.25 mm
Interior coating	50 nm sputtered iridium
Number of modules	16 (2)
Effective area	~200 cm^2 at 40 keV, (4 cm^2) 120 cm^2 at 60 keV
Angular resolution	15″ HPD (45″)
Field of view	9′ at 40 keV (6′) 5′ at 60 keV

Note.—Demonstration flight configuration in parentheses.

3.2. *Focal-Plane Detectors*

The current focal-plane detectors for the HERO payload are gas scintillation proportional counters (GSPCs). The GSPC offers a good combination of energy resolution, spatial resolution, and low background. These detectors are well developed for low-energy applications, and extension to higher energies is simply a matter of increasing the fill-gas pressure; our detectors use a xenon/helium (24/1) mixture at a total pressure of 10 atm (Austin et al. 1999). The measured performance, 350 μm spatial resolution and 5% energy resolution (FWHM) at 30 keV, is that expected from extrapolation of published data at lower pressures. The use of all stainless-steel and ceramic internal components, plus the addition of a purifying getter, ensures that the detectors will operate stably for long periods. The current units have now operated for over a year without any measurable deterioration.

3.3. *Balloon Gondola*

To exploit the full potential of the HERO optics necessitates a balloon gondola that can provide commensurate pointing accuracy, stability, and pointing knowledge. The HERO gondola utilizes a coarse aspect system for slewing based on a differential global positioning system (GPS) and a fine inertial-mode pointing system that uses a novel day/night aspect camera system to update onboard gyroscopes. The silicon-CCD aspect camera operates in the far red ($\geq$600 nm) and utilizes a very small field of view (8″ × 8″) per pixel to resolve stars against the overlying daytime sky background (Dietz et al. 2001). Calculations based on an Air Force model (MODTRAN) of the atmosphere estimated the camera's limiting daytime sensitivity to be around 9th magnitude in a 0.25 s exposure, enough to ensure several resolved stars in the camera's 6 deg^2 field of view for any star field. An onboard star catalog is used to compare with resolved images and to calculate any pointing offsets. These in turn are used to update the gyro drift rates to keep the target in the center of the field of view.

The mirror modules are mounted on a carbon-composite optical bench truss and aligned via a fine-screw-thread tip/tilt system. The truss tubes are wound to have near-zero thermal expansion along their length to provide stability over the fairly large temperature variations (~60° C) experienced in flight. An onboard laser alignment monitor system keeps track of any movement of the optics with respect to the focal-plane detectors.

To accommodate the full 6 m focal length, while permitting enough room for the azimuth drive mechanisms at the top and focal plane detectors at the bottom, necessitates a deployable optical bench to prevent the gondola becoming too unwieldy to launch. This will be done by splitting the bench into two halves: a mirror optical bench of 3 m length and a detector bench of similar length. The elevation flange around which the whole assembly tips will be in the middle. Only the detector part, at the base of the gondola, will deploy (be driven down) after launch.

For our recent test flight, we utilized only the upper mirror optical bench and the specially fabricated 3 m focal length optics. This enabled us to test the pointing system while we develop the deploying lower bench mechanism.

4. FLIGHT DATA

The test payload was launched from the National Scientific Balloon Facility at Fort Sumner, NM, on 2001 May 23 and spent approximately 17 hr at a float altitude of 39 km during the day and 37 km at night. During this time, the hard X-ray telescopes were pointed at the Crab Nebula, Cyg X-1, and GRS 1915+105, where they captured the first high-energy focused images of cosmic sources. One of these, Cyg X-1, is shown in Figure 1. The field of view shown is a square, 12$'\!.5$ on a side and the data are from the 20–45 keV energy band. The source was detected at just under 8 σ using both telescopes with 1 hr of data. The Crab Nebula and pulsar was seen at a similar significance level. GRS 1915, which is highly variable, was also detected at just under 6 σ during a 45 minute active period.

The test flight confirmed the stability of the optical bench and the ability of the attitude control system to hold X-ray targets with sufficient stability for extended periods of time. During the observation of Cyg X-1, for example, 33% of the observing time was spent within 30$''$ of the desired pointing direction and 60% within 1$'$. It is expected that refinements in software and additional filtering of the gyro signals will improve this on future flights. The day/night visible star aspect camera achieved a limiting daytime sensitivity of 8–8.5 mag, giving, e.g., 11 stars visible in the Crab field. The corresponding aspect solution was at the 8$''$ level.

5. CONCLUSIONS

The HERO payload, together with other balloon-borne hard X-ray focusing telescopes currently under development (Harrison et al. 2000; Tamura et al. 2000), will open up the hard X-ray region for sensitive exploration. When completed, HERO will provide fine imaging of X-ray sources at energies up to 75 keV with a sensitivity more than an order of magnitude greater than current nonfocusing hard X-ray instruments. This will make hundreds of sources accessible for study in conventional one-day balloon flights (10^4 s integrations) and more than an order of magnitude more on planned 100+ day ultralong-duration flights. Our recent proof-of-concept flight confirmed the viability of the replicated optics and the functioning of the necessary gondola subsystems. The full HERO science payload is planned for completion in late 2003.

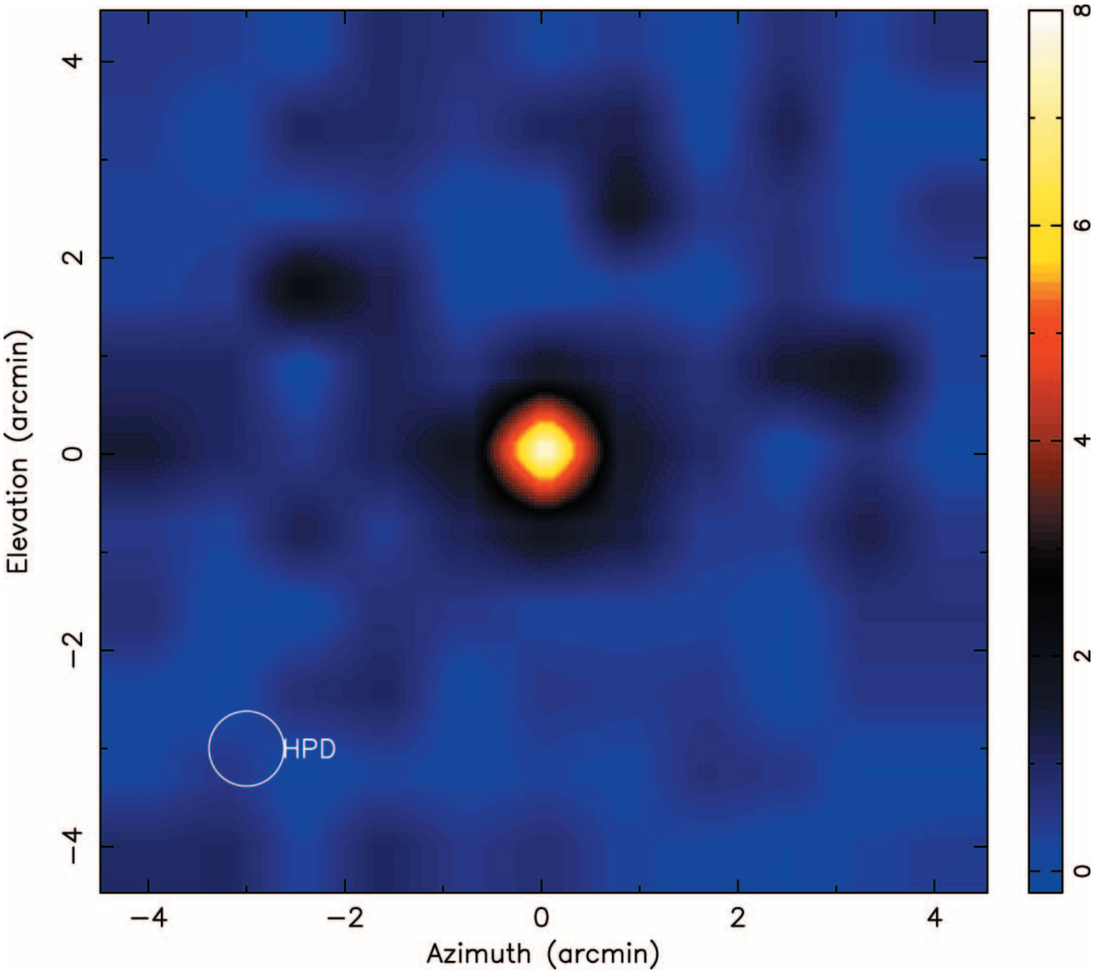

Fig. 1.—Hard X-ray (20–45 keV) focused image of Cyg X-1, smoothed with a 30$''$ boxcar filter. Circle shows the system half-power diameter (45$''$). Color depicts the significance level.

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