InFOCμS balloon-borne hard x-ray experiment with multilayer supermirror x-ray telescope

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ABSTRACT

We have been developing the high throughput hard X-ray telescope, using reflectors coated with the depth graded multilayer known as supermirror, which is considered to be a key technology for future satellite hard X-ray imaging missions. InFOCμS, the International Focusing Optics Collaboration for μ-Crab Sensitivity is the project of the balloon observation of cosmic hard X-ray source with this type of hard X-ray telescope and CdZnTe pixel detector as a focal plane imager. For the first InFOCμS balloon experiment, we developed the hard X-ray telescope with outermost diameter of 40cm, focal length of 8m and energy band pass of 20 - 40 keV, for which Pt/C multilayer was used. From the pre-flight X-ray calibration, we confirmed its energy band and imaging capability of 2 arcmin HPD and 10 arcmin FOV of FWHM, and a effective area of 50 cm^2 for 20 - 40 keV X-ray. We report the current status of our balloon borne experiment and performance of our hard X-ray telescope.

Keywords: Hard x-ray, optics, multilayer, supermirror

1. INTRODUCTION

Focusing optics in hard x-ray region above 10 keV will open a new window of the universe, where extremely hot astrophysical phenomena or non-thermal high energy phenomena like jet occur in unknown way. In contrast to great success of telescope in low energy band below 10 keV as verified by new observatories of Chandra and XMM-Newton, it has been difficult to make ordinary telescope for hard x-rays due to very low reflectivity of total reflection mirror. However, a recent progress of a multilayer supermirror and imaging hard x-ray detector combining high throughput telescope like ASCA and ASTRO-E can provide us hard x-ray focusing optics. In this paper, we report on the first attempt to a realize such new telescope. We made Pt/C supermirror hard x-ray telescope with the CdZnTe pixel detector as a focal plane instrument for balloon experiment for the first time, which is called InFOCμS project.

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2. INFOCμS PROJECT

International Focusing Optics Collaboration for μ-Crab Sensitivity (InFOCμS) , is a project to observe the hard x-ray sky with a new type of balloon-borne telescope utilizing multilayer supermirror. This project has been performed by the collaboration between the Goddard Space Flight Center, Nagoya University, ISAS and Arizona State University. The first balloon flight was done on July 5-6, 2001 to demonstrate viabilities of this project. Since focusing optics can provide not only imaging capability for extended hard x-ray source, but also high sensitivity because of very low background due to small detector volume in comparison with non-imaging instrument, all weak hard x-ray source can be science objectives generally. Possible targets for InFOCμS project after beeing verified its viability are listed in table 1.

Table 1. InFOCμS : Science Objectives

· Image ^{44}Ti nuclear lines in young SNR
· Image sites of cosmic ray acceleration in young SNR
· Image diffuse non-thermal emission and/or detect weak AGN from clusters of galaxies
· Detect radio lobes of AGN jets and measure the intergalactic magnetic field
· High resolution pulse-phase spectroscopy of cyclotron lines with unprecedented sensitivity and detection of higher harmonics
· High resolution studies of hard X-ray tails from neutron stars and black holes
· Determine the origin of the bump in the hard X-ray background by direct imaging of faint AGN
· Qualitative improvements in sensitivity. imaging, and resolution always result in unpredicted new discoveries

3. INFOCμS PAYLOAD

For the first flight of InFOCμS, one hard x-ray telescope for 20 - 40 keV energy bandpass with 40 cm outermost diamter and 8 m focal length was mounted on the optical bench, of which the structure is a open framework truss of carbon-fiber struts.

This optical bench is pointed by azimuth-elevation control drived with flywheel and ball screw actuator mounted on the same gondola structure as has been used for GRIS project. The attitude of the telescope is measured by the star camera, combinig data from inclinometer, magnetometer and rate integration gyros. Star camera updates of the absolute pointing direction every 12.5 s.

At the focal plane of the hard x-ray telescope, the CdZnTe pixellized detector called SWIN was used for the first flight. The pixel size is 2 mm square and 128 pixels covers 25.2 x 25.2 mm square focal plane except for each 4 pxisels at 4 corners, corresponding 0.9 arcmin pixel and 11 arcmin FOV angular size, respectively. The detection efficiency at 20-40 keV energy band is 100 % for 2 mm thick SWIN CZT and energy resolution is expected to be about 5 keV. To reduce non-sky backgound, 2.5 cm thick CsI active shield with 10 x 10 deg FOV was used. Parameters of the payload for the first InFOCμS flight is summarized in table 2.

4. THE HARD X-RAY TELESCOPE

One of the key instruments of InFOCμS project is the hard x-ray telescope, which utilized depth graded multilayer, so called supermirror, for the first time. For the first flight of InFOCμS, we chose Pt and C as multilayer materials and their multilayer parameters of d_i (i-th bilayer thickness) and Γ (the ratio of Pt-layer thickness and d_i) were determined to get maximum integrated x-ray reflectivity in 20 - 40 keV. From a practical point of view, we use same parameters for same group of foil mirrors, where 255 foil mirrors with different radii were divided into 13 groups in order of radius (60 mm to 200 mm) or corresponding incident angle (0.15 deg to 0.35 deg). Small total bilayer number was also taken into account for the same practical reason. This concept was verified by the demonstaration model (Yamashita et al. 1998) and details of our design were described in our previous papers(Tawara et al. 1997, Yamashita et al. 1999b, Owens et al. 2000, 2001).

Table 2.

Hard x-ray telescope:	Focal length	8m
	Energy bandpass	20-40 keV
	Number of foil mirror nesting	255
	Range of diameters of mirrors	12 - 40cm
	Effective area	50 cm^2
	Field of View	9 arcmin (FWHM)
	Angular resolution (HPD)	2 arcmin
Focal plane detector:	Material	CdZnTe
	Pixel size	2mm x 2mm
	No. of pixels	128
	Detector size	25.2mm x 25.2mm
Gondola:	Pointing sysytem	AZ-Elevation control by Flywheel and ball screw actuator/
	Pointing	

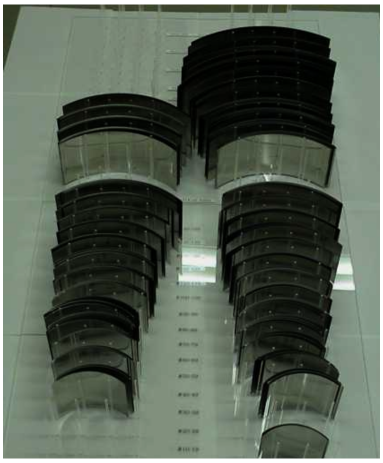

Figure 1. Replica foil mirrors coated with multilayer supermirror for the first flight of InFOCμS balloon-borne hard x-ray telescope.

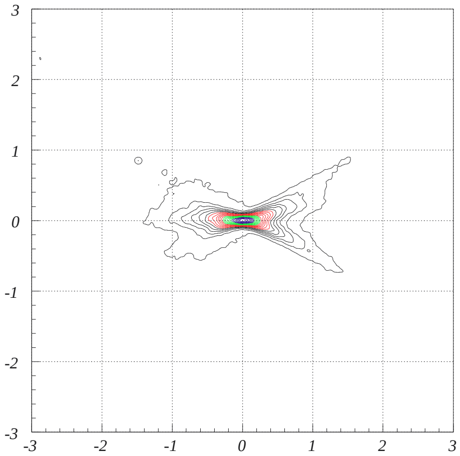

Figure 2. The point spread function of the second quadrant telescope for Cu-K X-rays

The base of the supermirror for InFOCμS is a replicated thin foil mirror developed for ASTRO-E x-ray telescope (Serlemitsos et al. 1995, Soong et al. 1995). We used two ways of supermirror fabrication, one is the coating multilayers on replica foil mirror and another is the direct replication of multilayer coated on a glass mandrel(Furuzawa et al. 1998, Owens et al. 2000). The deposition of Pt/C multilayer for supermirror coating on the replicated foil mirrors was done by a DC magnetron sputtering sysytem (Tawara et al. 1997 and Tamura et al.).

Based on the above described method, we made totally 2040 segmented foil supermirror for one full telescope, a half of them by Nagoya group and another half by GSFC group. It took about 9 months for mass production process of supermirror coating using two sputtering sysytem in Nagoya group. Averaged turn around time ranged from 4.3 hours for innermost foils to 8 hours for outermost foils. We checked the quality of multilayer by measuring x-ray reflectivity of at least one sample among foils in one batch of deposition. We found that absolute d-spacings at the center of each foil mirror were controlled within 2 %. Uniformities of d-spacing in each foil were less than 4 % in optical axis direction and less than 10 % in azimuthal direction. Averaged interfacial roughness was 0.40 nm and 95 % of measured data ranged from 0.3 to 0.5 nm.

5. PRE-FLIGHT CALIBRATION

After completion of segmented 2040 foil mirrors, 4 quadrants telescope were assembled in the same way as taken for ASTRO-E x-ray telescope and tuned to have a focal length of 8 m and the best point spread function under a optical parallel beam. Then we measured basic performance of each quadrant telescope in several different ways. On the imaging capability, we first measured on axis point spread function using Cu-K 8.1 keV line and X-ray CCD as an imaging detector at ISAS 40 m beam line. Since this beam line didn't have enough length between sample telescope and detector to hold its focal length of 8 m, we move a telescope and a detector so that a detector can collect x-rays in mid course correctly. The PSF of 2nd quadrant telescope prepared by Nagoya group is shown in figure 2. It was found that HPD's of two quadrants prepared at Nagoya group were both 2.1 arcmin, which is similar to those of ASTRO-E quadrant telescope.

5.1. X-ray Measurement

We also measured the energy dependent effective area for on-axis x-rays using continuum emission from tungsten target of x-ray generator and NaI scintillation counter. Figure 3 shows one of such results for second quadrant prepared by Nagoya group, together with calculated curves for the assumed interfacial roughness sigma of 0, 0.3, 0.38 nm, where 0.38 nm corresponds to the averaged value derived from the measurement of x-ray reflectivities for each replica foil mirrors. We found that large difference between measured and calculated effective area by factor of 0.4, but energy dependence of this difference was relatively small. To get further information on this ploblem, we also performed the measurement of x-ray reflectivity using very small x-ray beam with diameter of 50 μm. Figure 4 shows an example and found that there is no clear radius dependence of reflectivity.

After evaluation of each quadrant performance, we assembled all quadrants to one full telescope and adjusted quadrants position and direction under the ilumination of optical parallel beam. We evaluated the integrated telescope performance of the effective area and imaging quality, using x-ray raster scan testing facility (Owens et al. 2001) at NASA/GSFC. Then we mounted the telescope on the top plate of the optical bench and the hard x-ray detector on the another end of optical bench. For this integrated system, the final ground calibration of end-to-end test was performed also using x-ray raster scan testing facility. From this measurement, we confirmed that basic performance is consistent with each quadrant measurement. Details of the results of both measurement are described in Owens et al. 2001.

Based on the result of the ground calibration, we calculated the sensitivity of discrete source detection as shown in Figure 5.

6. FLIGHT TELESCOPE ASSEMBLY AND ALIGNMENT

Flight telescope, a star camera and a detector were mounted on an optical bench, a light weight truss system using carbon fibre tubes(figure 6). Though the telescope and the star camera are on the same top plate(figure 7), the directin of the star camera field center is 45 degree apart from that of the telescope field center to avoid an obsculation of the field of view by balloon itself, which is transparent to hard x-rays. To avoid contamination of dust in the test launch field, we covered two 1.5 mm thick acrylic plate, of which x-ray transmission for 20 keV is 85 %. We masked 1-st and 14-th sector of each quadrant telescope with 0.5 mm tin to reduce an image blur due to bad mirror shape at open end of foil mirror(figure 8). To avoid thermal distortion of replica foil mirrors, we use heater control system to keep mirror temperature around 15 C.

After setting these optics, we did pre-launch alignment between x-ray telescope and star camera using look-up camera, which is temporally mounted at the center of the telescope to see stars in the night sky from the ground. We also calibrated inclinometers, gyros and magnetometers to determine the aspect. Details will be described in the separate paper.

7. FIRST FLIGHT AND FUTURE PLAN

Before completion of this manuscript, the first balloon flight has been done. The balloon was launched at NASA/NSBF at Palestine, Texas on July 5th 8:10 p.m. CDT (July 6, 1:10 UT) and it reached level flight at an altitude of 40 km at 0:15 a.m CDT. The level flight continued for 2.8 hours. We confirmed that the focal

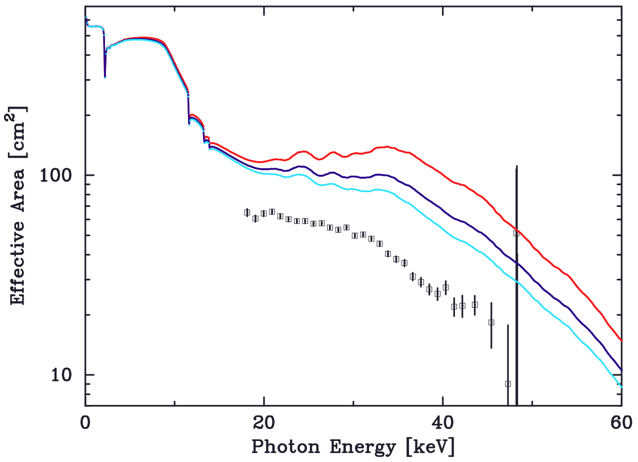

Figure 3. Effective area of 1-st InFOCμS X-ray telescope. Open circles show measured value of the 2nd quadrant multiplied by 4. Curves are calculated for designed parameters assuming interfacial roughness of 0.0, 0.3 and 0.38 nm for top, middle and bottom curves, respectively.

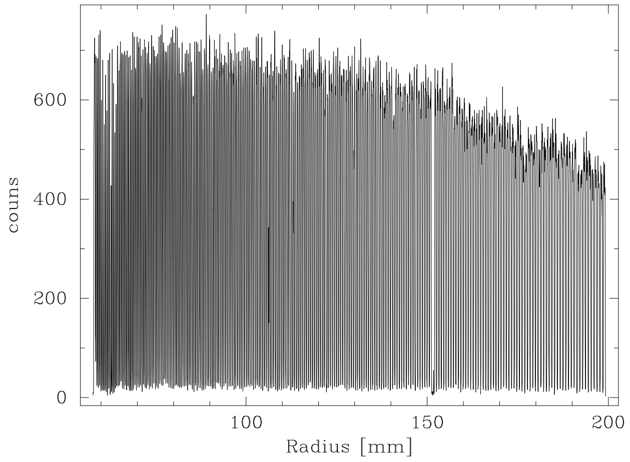

Figure 4. Reflected beam intensity profile of each foil mirror of InFOCμS X-ray telescope, where X-ray beam energy is Cu-K 8.1 keV and beam diameter is 50 μm.

plane detector worked properly during the fllight. The primary and only target for this flight was Cyg X-1 and detailed data analysis will be done hereafter and will be published in a separate paper.

For the future plan of InFOCμS experiment, we are planning second flight next year. Major improvements and developments having to be done for the second flight are as follows; i) to investigate the discrepancy between calculated effective area and measured one and increase the area, ii) to extend energy band higher than 40 keV, iii) to get better image quality than 2 arcmin HPD, iv) to improve pointing sysytem.

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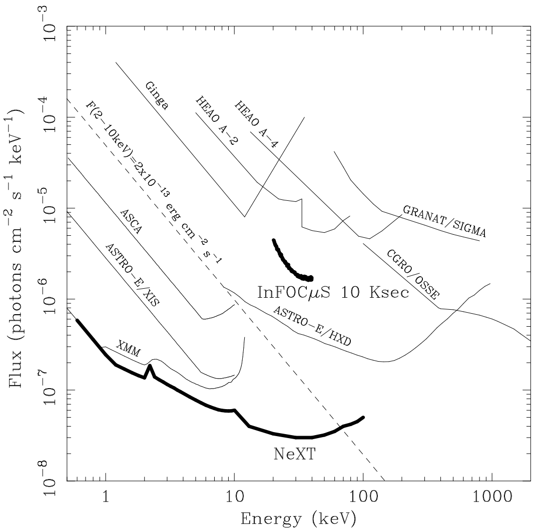

Figure 5. Detection limit of 1st InFOCμS flight for assumed 10ks exposure, with comparison to the past experiment. All the past experiments above 10 keV were used non-imaging detectors. A sharp upturn of InFOCμS detection limit towards low energy end is partially due to atmospheric absorption at the balloon altitude of 40km.

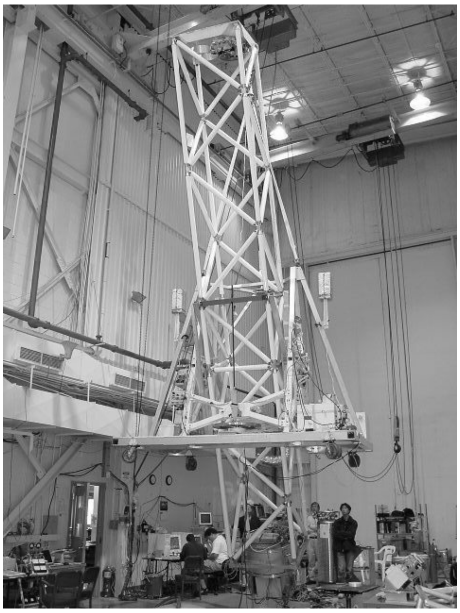

Figure 6. The 1st InFOCμS flight gondola. An optical bench for the X-ray telescope with 8m focal length is a light weight truss system using carbon fibre tubes.

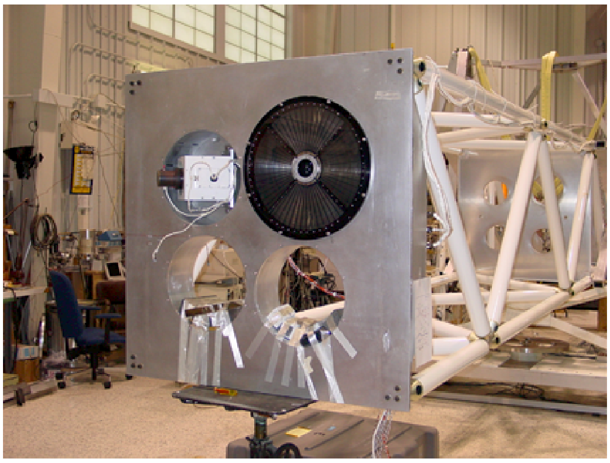

Figure 7. The top plate of the optical bench. For the 1st InFOCμS flight, one full hard X-ray telescope and the star camera are mounted on the top plate.

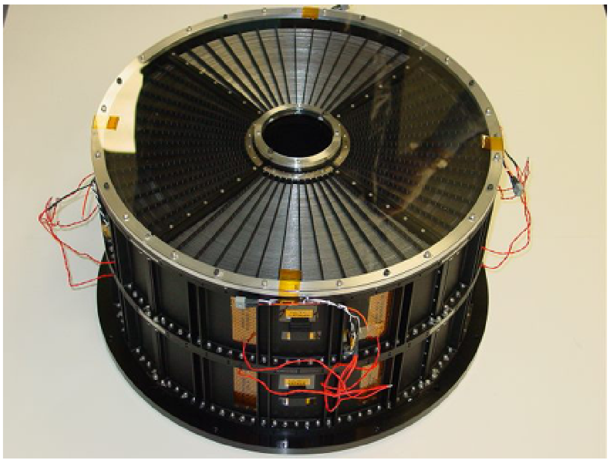

Figure 8. The assembled flight hard X-ray telescope for the 1-st InFOCμS experiment.