Development of Astronomical Hard X-ray Telescope and Its Characterization using High-brilliance Synchrotron Radiation Facility

It is usually thought that astronomers observe the sky with high resolution, much finer than our naked eyes. Unfortunately, it is not the case in some span of electromagnetic spectrum, where one cannot even tell the difference between the moon and a star, because of a lack of spatial resolution. In our research, we aim to bring optics into the hard X-ray spectrum region, where no one has ever observed the Universe with high spatial resolution. The key technologies of "hard X-ray telescope" are multilayer-supermirror hard X-ray reflector and multi-nested high-efficient grazing incidence optics.

An X-ray telescope utilizes grazing incidence optics called Wolter-I system. The principle of X-ray reflection is the total external reflection that occurs only at grazing incidence. Since the late 1970s, many X-ray telescopes have been installed on orbiting satellites and facilitated scientific achievements. These telescopes were, however, only sensitive below 10 keV, due to the practical limit of the use of total external reflection in terms of aperture efficiency and field of view.

Instead, Bragg's reflection by multilayer is the effective principle of reflection beyond 10 keV. When the periodic length of a multilayer is graded in the depth direction, the so-called "supermirror," Bragg's condition is satisfied in a wide range of X-ray energies at a fixed angle. Wide energy and angular response are key requirements for astronomical instruments. Developments have been underway since the mid-1990s by several research groups in the world, as one of key technologies for the next generation X-ray observatories. See Yamashita *et al.* [1] for general reviews, as well as some of our initial works.

We chose platinum-carbon combination as the multilayer supermirror, because of platinum's high-electron number density and carbon's sharp interface against platinum. Multi-nested thin-foil optics is employed to achieve high efficiency. Technical details have been reported in previous papers [1-3]. Figure 1 shows a photograph of the hard X-ray telescope thus fabricated. The aperture diameter, height and focal length are 40 cm, 20 cm and 8 m, respectively. 255 pairs of optics are nested coaxially and con-focally in the telescope housing. About 2000 segmented reflectors are used for one telescope.

Fig. 1. Multilayer supermirror hard X-ray telescope.

The telescope was first characterized at beamline **BL20B2**. This characterization part of the study is quite important. Otherwise, telescope performance will remain unknown and data observed from the sky will remain difficult to interpreted. In addition to synchrotron light brightness, BL20B2 has a 200-m-long transport tube. Therefore, large-sized and less divergent beam is available, which is a crucial requirement for measuring large aperture optics.

Figure 2 shows an example of an X-ray image focused by our hard X-ray telescope and measured using a CCD-based hard X-ray imager at 30 keV. Such measurement was performed with 10 to 80 keV X-rays. The measurement showed that hard X-rays are successfully focused, with a quality of 2.5 arcmin in terms of Half Power Diameter. The number is almost the same as that measured at 8 keV prior to this experiment. This is an experimental proof that the same quality of angular resolution as in the soft X-ray region is attained by our method.

The high brightness of the beam at SPring-8 enables us to perform microscopic measurement of the telescope. It is important to "diagnose" the telescope and not just to "characterize" it to know how current performance is established, or what prevents the telescope from performing better than its present performance.

Figure 3 is what we call as "local brightness distribution" measured at various energies. We divide the telescope aperture into about 2000 local areas in r-φ plane, and each area is illuminated by X-rays. Focused images are measured for each area. The color coding of each figure indicates an X-ray flux obtained from each measurement. The wedge-shaped dark areas correspond to boundaries between neighboring mirror segments (quadrants). The radial slope of flux is observed, as well as the dependency of its steepness on energy. They agree well with the angular and energy reflectivities of supermirrors. Segment-to-segment

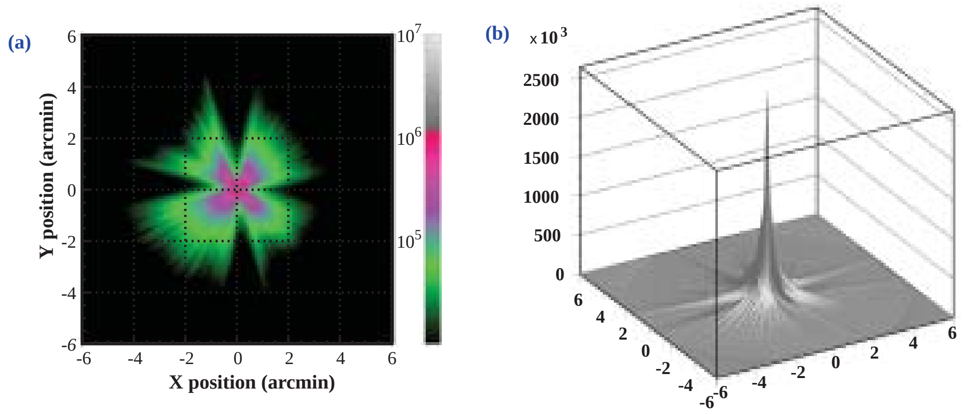

Fig. 2. Focused image of hard X-ray telescope at 30 keV. **(a)** Two-dimensional expression with color coding in log scale. **(b)** Three-dimensional expression. Horizontal axes are in arcmin.

difference comes from the difference of supermirror designs. These verifications are so-called "function check." In terms of "diagnostics," any local anomalies of brightness, for example, dark lanes in the upper-left and lower-right quadrants as seen in the figures, are indicative of reflectors not functioning well in these areas. Information obtained is enormous, and is used for understanding and improving the telescope. These functions are brought about by the bright light source, and cannot be totally attained without bright synchrotron light and a beamline with long baseline. Recent results are summarized in the study of Ogasaka *et al.* [4].

The telescope, the first of its kind when launched on the stratospheric balloon payload for its first flight in 2001, and still the largest in effective area as a single unit, was dedicated for successful scientific flight observation in 2004 [5]. The experiment was carried out by US-Japan international collaboration (InFOCμS project [6]). In this flight, we observed multiple astronomical objects from nearby black holes in our Milky Way galaxy, to distant (about one billion light years away) cluster of galaxies that harbor tens or sometimes even hundreds of galaxies like our own. Data analysis is underway, and part of the data confirmed the function of our telescope. Although we have many steps to go before we can establish truly epoch-making scientific results, a new window is now open in the hard X-ray spectrum region.

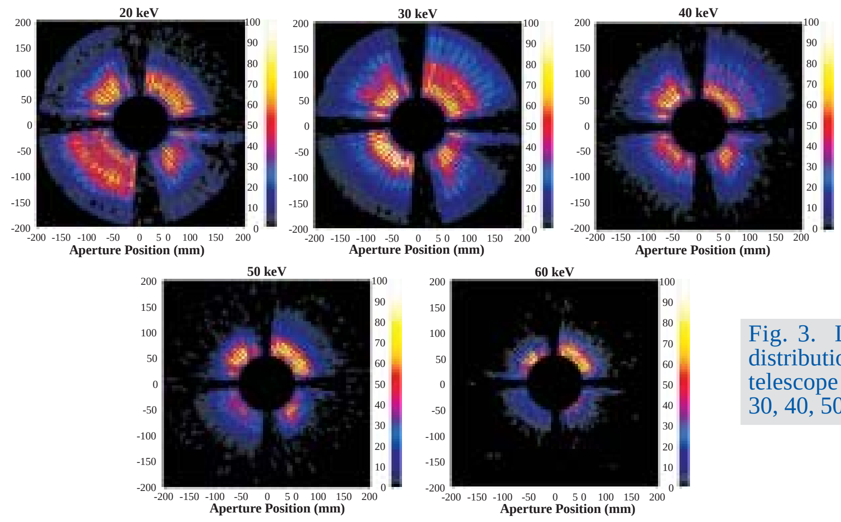

Fig. 3. Local brightness distribution of hard X-ray telescope measured at 20, 30, 40, 50 and 60 keV.

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