Hard X-ray and Gamma-Ray Detectors for the NEXT mission

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Abstract

When compared with X-ray astronomy, the gamma-ray astronomy, especially in the energy band from 10 keV to several MeV, is still immature and significant improvements should be done to obtain sensitivity comparable to that achieved in the energy band below 10 keV. In order to fill this "sensitivity gap", the NeXT (New X-ray Telescope) mission has been proposed as a successor of the Astro-E2 mission. The high-energy response of the super mirror will enable us to perform first sensitive imaging observation up to 80 keV. One idea for the focal plane detector is to combine a fully depleted X-ray imaging device (soft X-ray detector) and a pixelated CdTe (Cadmium Telluride) detector. In the soft gamma-ray band upto ~ 1 MeV, a narrow field-of-view Compton gamma-ray telescope utilizing several tens of layers of thin Si or CdTe detector has been proposed to obtain much higher sensitivity than present instruments.

1   Introduction

The hard X-ray and gamma-ray bands are important windows for exploring the energetic universe. It is in these energy bands that non-thermal emission, mostly due to accelerated high energy particles, becomes dominant. In fact, the results from recent cosmic X-ray observatories have shown that sensitive observations in these high energy bands are necessary to constrain the continuum spectra of many classes of X-ray sources. However, the lack of sensitive instruments in these energy ranges prevents us from further studying the non-thermal spectra. Therefore, hard X-ray and gamma-ray instruments in the 21st century should provide much improved sensitivity for both point and extended sources over the instruments in use today. The NeXT (New X-ray Telescope) mission planned at ISAS (the Institute of Space and Astronautical Science) is a successor to the Astro-E2 mission, with much higher sensitivity in the energy from 0.5 keV to $\sim$ 1 MeV. The first imaging observation up to 80 keV with a focusing telescope will open up a new window to explore the non-thermal universe. Here we describe current ideas about hard X-ray detector and soft gamma-ray detectors proposed for the NeXT mission.

2   Hard X-ray Observation with a super mirror and CdTe pixels

In the 10-100 keV band, the most promising approach to improve the sensitivity is to extend the energy coverage of the focussing telescope to higher energies. This could be achieved by a multi-layer, grazing incidence hard X-ray mirror ("super mirror") (Yamashita et al., 1998) in conjunction with a hard X-ray imaging detector. In addition to the imaging capability, the small volume of the focal-plane hard X-ray detector significantly reduces the background, since the background flux generally scales with the size of the detector. In order to match the energy range covered by the super mirror (0.5 - 80 keV), the focal plane detector is required to cover a very wide energy band. One idea is to stack a fully depleted solid-state imaging detector in soft X-rays such as an X-ray CCD above a pixelated CdTe detector (Takahashi et al. 2000). For this, we have been working on research and development of the high performance CdTe detectors (Takahashi et al. 2001). An energy resolution of 1 keV (FWHM) is obtained with the CdTe diode with an area of 2 mm $\times$ 2 mm and a thickness of 0.5 mm, operated at 5 °C . The technology for gold-stud bump bonding suitable for CdTe/CdZnTe semiconductor has been developed and used to connect each pixel to the fanout board consisting of bump pads and patterns to route the signal from the pad or the ASIC itself. With this technology, we have developed prototype pixel detectors with an array of 16$\times$16 pixels using a with pixel size of 2$\times$2 mm^2 and 64$\times$64 pixel detector with pixel size of 200$\times$200 μm^2.
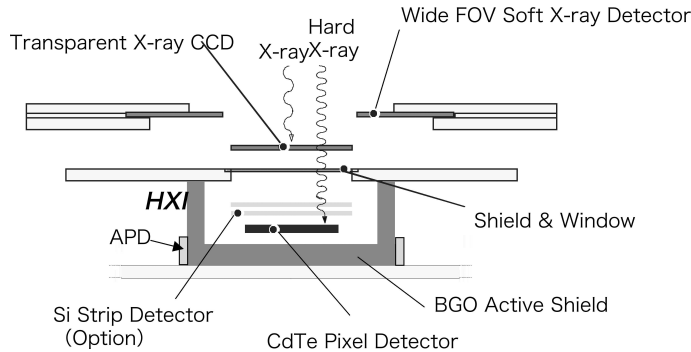
Fig. 1. Schematic of the hybrid detector proposed for the NeXT. The CdTe pixel detector is placed underneath the X-ray CCD. The Si strip detector is to shield fluorescence lines from CdTe.

Figure 1 shows a schematic design of the Hard X-ray Imager (HXI), proposed as the focal-plane detector for the super mirrors. Soft X-rays will be absorbed in the CCD, while hard X-rays will penetrate the CCD and be absorbed in the CdTe pixelated array. In the latter device, pixel electrodes are formed on the surface of CdTe and each electrode is bump-bonded to the readout electronics chip. In order to obtain the ultimate sensitivity for hard X-ray enegy, we incorporate active shielding by BGO crystal. The detectors will have a fast timing resolution of 10 to 100 μs, so that we can veto the signal when there is a hit in the active shield. With NeXT, we expect to achieve an area of about 500 cm^2 at 30 keV with a typical angular resolution of a spot of 30". For a power-law spectrum with photon index of 1.7, the source detection limit in 100 ksec (assuming a negligible background in the source region) would roughly be 10^{-14} erg cm^{2}s^{-1} in terms of the 10-40 keV flux, i.e. two orders of magnitude lower than the present instrumentation.

3   Narrow FOV Compton telescope

In the energy range above hundred keV (sub MeV region), shielding against background photons becomes important yet difficult. The phoswich config-uration and a tight and active "well-type" shield, which we developed for the Astro-E Hard X-ray Detector (HXD) (Tashiro et al. 2002, Makishima et al. 2002) is a solution to achieve a very low background rate. The well-type shield made of BGO scintillators, which surrounds the detection part (GSO scintillator) is expected to reduce the background to the limit achieved by the configuration of active shield and collimator.

In order to further reduce the background and thus to improve the sensitiv-ity, we have proposed a new detector called the Soft Gamma-ray Detector (SGD) for the NeXT mission, which utilizes the idea of a narrow FOV Comp-ton telescope (Takahashi et al. 2002) for the NeXT mission as illustrated in

Fig.2, In the SGD, we combine a stack of Si strip detectors and CdTe pixel detectors, to form a Compton telescope, which is mounted inside the bottom of the well-type active shield. Firstly, the stack configuration and individual readout provide informations of the interaction depth. This depth information is very useful to reduce the background, because we can expect that low energy gamma-rays interact in the upper layers and, therefore, we can reject low energy events detected in lower layers. Moreover, since the background rate is proportional to the detector volume, low energy events collected from the first few layers in the stacked detector have a high signal to background ratio, in comparison with events obtained from a monolithic detector with the same thickness as the sum of all layers.

Important feature of the SGD is that we can require each SGD event to interact twice in the stacked detector, once by Compton scattering in the Si part, and then by photo-absorption in the CdTe part (Compton mode). Once the locations and energies of the two interactions are measured, the Compton kinematics allow us to calculate the angle between the telescope axis and the incident direction of the event. The high energy resolutions of the Si and CdTe devices help reducing the width of these "Compton rings". We can determine the location of point sources as intersections of multiple rings, although the angular resolution is limited to $\sim 1 deg$ at 300 keV due to the finite momentum of the Compton-scattering electrons (Zoglauer and Kanbach 2002). Regarding to the reconstruction of the order of the scattering, we can use the relation that the energy deposition by Compton scattering is always smaller than that of the photo absorption for energies below $E_\gamma = 255$ keV ($E_\gamma = m_e/2$). This relation holds above this energy, if the scattering angle θ is smaller than $\cos^{-1}(1 - \frac{1}{2}\frac{m_e}{E_\gamma})$.

The major advantage of employing the Compton kinematics, however, is to reduce the background. By having a narrow FOV, and by requiring the Compton ring of a valid aperture gamma-ray event to intersect with the FOV, we can reject most of the background events. Particularly, this is expected to drastically reduce the background from radio-activation of the detector materials, which becomes a dominant background in the case of the Astro-E HXD. Furthermore, we can eliminate Compton rings produced by bright sources located outside the FOV, which would produce significant background without the narrow FOV. The narrow-FOV design of the SGD is matched to the main objective of the NeXT mission, i.e., the use of the super mirror coupled to the HXI.

We are studying the optimum configuration of the geometry to be used in the SGD based on the currently available Si and/or CdTe imaging devices (Takahashi et al. 2003, Tajima et al., 2003). The efficiency of the SGD when employing 24 layers of 0.5 mm thick Si double strip detectors and a 6 mm-thick CdTe pixel detector is shown in Fig. 3 (b). The line and continuum sensitivities of the SGD and the HXI for 100 ks observation are shown in
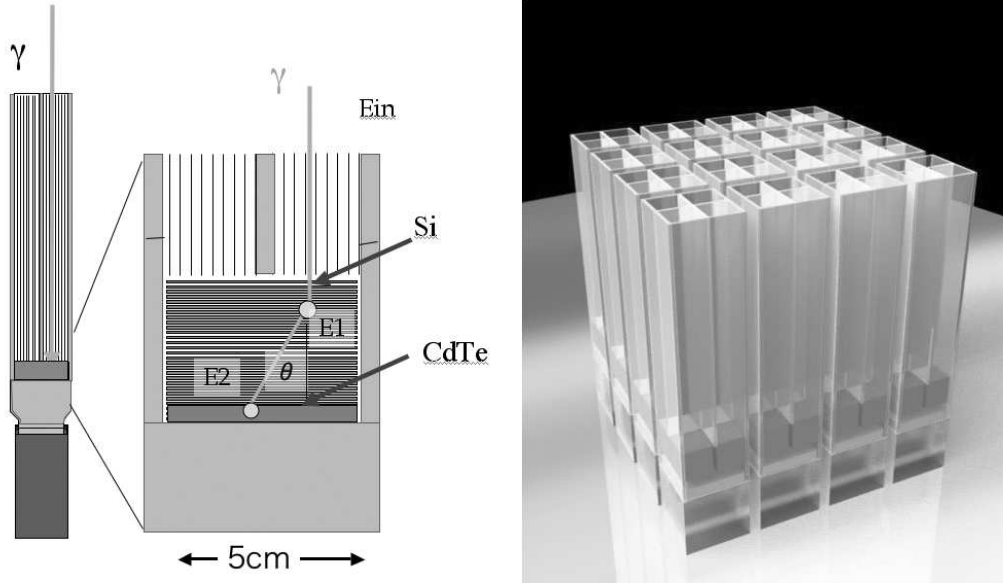
Fig. 2. A conceptual design of the narrow FOV Compton telescope, composed of a stack of 24 silicon double strip detectors and a CdTe pixel detector. Both are buried in a deep BGO well (left). That of the SGD employing 16 units of the Compton telescope (right). The geometrical area of 400 cm^2 is currently assumed for the sum of 16 units.
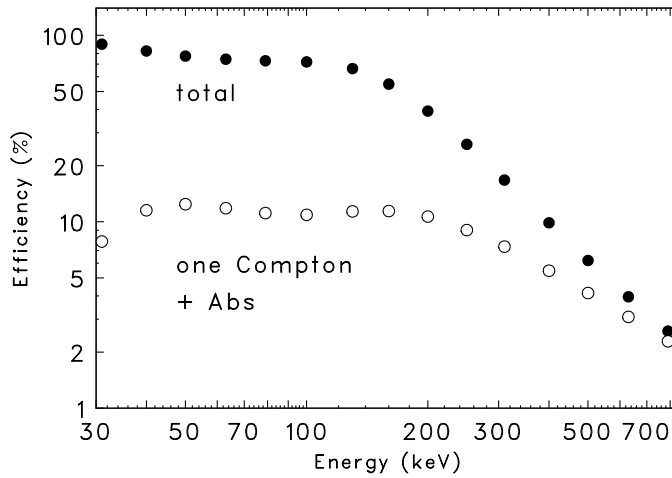

Fig. 3. Efficiency of the SGD shown in Fig. 2

Fig. 4, together with those of the HXI and other missions. With the SGD, we can also measure polarization of incident gamma-rays from the azimuthal distribution of Compton scattered photons. We may improve the lower-energy (below ~ 150 keV) angular resolution by incorporating coded-mask or Fourier-synthesis (Kotoku et al. 2003) optics.
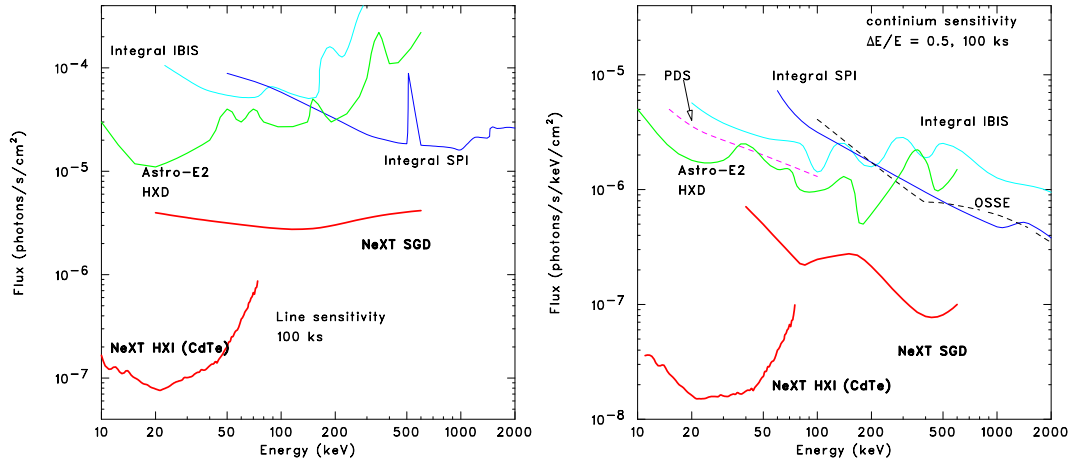
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Fig. 4. The expected HXI and SGD senstivities for line (left) and continuum (right) emissions, assuming an observation time of 100 ks.

4 Conclusion

Based on our recent achievements of high performance CdTe and Si imaging detectors, we have proposed the HXI and the SGD for the NeXT mission. By combining these detectors, we are expected to achieve the highest sensitivity ever in the hard X-ray and sub-MeV gamma-ray region for both line and continuum emission. The SGD will provide the capability of polarization measurements above 100 keV.

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