EXPLORING THE HARD X-/SOFT GAMMA-RAY CONTINUUM SPECTRA WITH LAUE LENSES

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Abstract

The history of X–ray astronomy has shown that any advancement in our knowledge of the X–ray sky is strictly related to an increase in instrument sensitivity. At energies above 60 keV, there are interesting prospects for greatly improving the limiting sensitivity of the current generation of direct viewing telescopes (with or without coded masks), offered by the use of Laue lenses. We will discuss below the development status of a Hard X-Ray focusing Telescope (HAXTEL) based on Laue lenses with a broad bandpass (from 60 to 600 keV) for the study of the X-ray continuum of celestial sources. We show two examples of multi-lens configurations with expected sensitivity orders of magnitude better (∼1×10⁻⁸ photons cm⁻² s⁻¹ keV⁻¹ at 200 keV) than that achieved so far. With this unprecedented sensitivity, very exciting astrophysical prospects are opened.

Key words: Instrumentation: gamma–ray lenses – X–rays: cosmic diffuse background – X–rays: galaxies – gamma–rays: bursts – gamma–rays: observations

1. Introduction

Energy spectra beyond 60 keV are now well determined only for the hardest and strongest sources in the sky. For most objects, even for the most powerful, above 70-80 keV the spectra are scarcely known (see examples in Fig. 1, Fig. 2).

However the >60 keV energy channel is crucial to study many open issues of high energy astrophysics. Among them, we wish to mention the following:

– The physics in presence of super-strong magnetic fields (mass accreting X-ray pulsars, anomalous X-ray pulsars, Soft Gamma–Ray Repeaters);
– High energy cut-offs of BH binaries and, more generally, high energy tails of compact X-ray binaries (low and high mass);
– Study of the hard X–/soft gamma-ray emission level from low and high mass X–ray binaries in quiescence;
– The role of Inverse Compton with respect to synchrotron or thermal processes in GRBs.
– The role of non thermal mechanisms in extended objects (supernova remnants, galaxy clusters).
– High energy cut-offs in the spectra of Active Galactic Nuclei (AGN).
– The origin of the high energy Cosmic X-/gamma-ray Background (CXB). Synthesis models (see, e.g., Fig. 3) require a spectral roll-over with an e-folding energy of 100-400 keV in AGN. So far only a few sparse measurements of these sources, mainly with BeppoSAX are

Figure 1. An example of the pulse-phase resolved spectrum of Her X–1 (corresponding to the fall of the 1.24 s pulse profile), obtained with BeppoSAX soon after an anomalous low–ON cycle which occurred in October 2000. The second harmonics of the cyclotron line is apparent, as is the low statistical quality of the spectrum above 70 keV. Reprinted from Orlandini (2005)
available. It cannot be excluded that a new source population, with a cut-off clustered around 100-400 keV, is responsible for the observed CXB spectrum. Much more sensitive observations than those performed with BeppoSAX at hard X-ray energies are urgent.

- Nuclear (e.g., $^{44}$Ti) and annihilation (511 keV) lines.

A more extended discussion of these issues was given in the proposal submitted in response to the ESA call for ideas for Cosmic Vision 2015–2025 "Exploring the hard X-/gamma–ray continuum sky at unprecedented sensitivity" by Frontera et al.).

2. DEVELOPMENT OF HIGH ENERGY (>60 keV) LENSES

Results of a feasibility study of a Laue lens with broad energy bandpass (typically 60–600 keV) have already been reported (Pisa et al. 2004). The technique adopted is Bragg diffraction from mosaic crystals. The geometrical configuration of the lens (see Fig. 4) is spherical, with sphere radius equal to 2 times the focal length $F_L$. The lens is covered by mosaic crystal tiles with sizes as small as possible (e.g., $10 \times 10$ mm$^2$ or less). The crystal tiles are positioned in the lens according to an Archimedes’ spiral. In Fig. 5 we show an example of this crystal tile disposition for a lens prototype which we are currently developing (see below). The Archimedes’ spiral geometry allows a smooth dependence of the lens effective area with energy. The size of the lens and thus its effective area scales with the square of the focal length. The adopted material is Cu (111), which we can produce with a mosaic structure of angular spread $\geq$ 1 arcmin (FWHM). Reflectivity test results (see example in Fig. 6) performed on samples of Cu (111) are consistent with the theoretical expectations (Pellicciotta et al. 2005). A hard X-ray facility (LARIX) for testing the Laue lenses is also being developed (Loffredo et al. 2005).

The development of a Demonstration Model (DM) is now in progress. It consists of 30 tiles of Cu (111) mosaic crystal with 5 arcmin (FWHM) mosaic spread and $15 \times 15$ mm$^2$ cross section. The goal is to establish the crystal assembling technique. The development of a prototype model (PM) with 500 crystals and 210 cm $F_L$ is already scheduled as the next step. The nominal energy band of the PM will be from 60 to 200 keV. In addition to the laboratory tests, the PM is also expected to be tested in a balloon flight.

The focal plane detector required for the Laue lenses should have a high detection efficiency in the entire range of operation of the lenses (almost all focussed gamma–rays should be detected), a spatial resolution $\leq$ 1 mm, an energy resolution (FWHM) $< 2$ keV at 500 keV for the study of the nuclear and annihilation lines, and a detector sensitive to the photon linear polarization. The polarization sensitivity is a key requirement given that most of the emission processes of gamma–ray radiation in the source classes mentioned in Section 1 are expected to partially produce polarized photons.

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**Figure 2.** The energy spectrum, obtained with BeppoSAX of the Seyfert 2 galaxy MKN 3 compared with that of the well known quasar 3C273. The peculiarity of MKN 3 (Compton thick AGN) with respect to 3C273 (unabsorbed AGN) is apparent, as is the low statistical quality of the two spectra above 100 keV. Figure kindly provided by M. Cappi.

**Figure 3.** Measurements of the CXB $E\Phi(E)$ spectrum compared with a synthesis model (Comastri 2004). In this model it is assumed that the CXB is due to the superposition of Compton thin ($22 < \log N_H < 24$, long-dashed curves) and unabsorbed ($\log N_H < 22$, short-dashed) AGNs, with two possible values of the high energy cut-off: 400 keV (blue lines), 100 keV (red lines). The model parameters are tuned in order that their superpositions (continuous lines) can account for 80% of the XMM (2-10 keV) measured CXB.
3. TWO EXAMPLES OF MULTI-LENS TELESCOPES

In order to show the expected capabilities of Laue lenses in the hard X-/soft gamma-ray band, we report here two possible configurations of multi-lens telescopes.

1. **Configuration 1** (see Fig. 4) with a focal length of 15 m and a nominal energy passband from 1 to 600 keV. It includes:

   - 1 Low Energy Lens (LEL) with a nominal passband from 54 to 200 keV;
   - 4 High Energy Lenses (HEL) with a nominal passband from 150 to 600 keV;
   - In the hole left free from the LEL, a Wolter I Multi-Layer (ML) optics, confocal with the latter, to cover the 1-80 keV energy band;

2. **Configuration 2** (see Fig. 5) with a nominal passband from 1 to 900 keV. It includes:

   - 1 low energy lens (LEL) with a nominal 54-200 keV passband;
   - 4 high energy lenses (HEL) with a nominal 150-600 keV passband;
   - 1 Nuclear Line Lens (NLL) devoted to specifically study nuclear lines in the two energy bands: 450-540 and 800-900 keV;
   - In the hole left free from the NLL, a Wolter I Multi-Layer (ML) optics (not shown), confocal with the latter, complements the lenses to cover the 1-80 keV energy band.

In configuration 2, ML mirrors and LEL and HEL lenses are assumed to have a focal length of 20 m and a mosaic spread of 2 arcmin, while the NLL lens is assumed to have a focal length of 80 m. The inconvenience of the very high focal lengths (> 30 m) is their requirement for a very small spread (< 1 arcmin) of the mosaic crystals, which is now much more difficult to produce. Multi-lens configurations with one single focal length are being investigated. A ray tracing code devoted to study the optical properties of the Laue lenses for offset incident beams is also in progress.

In Figs. 6 and 7 we show the expected 3σ sensitivity of the multi-lens Configurations 1 and 2 (only LEL and HEL), in which a crystal thickness of 2 mm for the LEL and 4 mm for the HELs was assumed. The crystal...
Figure 7. Top view of the multi-lens configuration 1, with 15 m focal length and a passband from 60 to 600 keV. In the hole left free by the low energy lens, a multilayer telescope is assumed, to extend the band down to $\sim 1$ keV.

Figure 8. Top view of the multi-lens configuration 2, with a passband from 60 to 900 keV. The LEL and the 4 HELs cover the band from 60 to 600 keV and have a focal length of 20 m; the lens devoted to detect nuclear lines (NLL) in the range 450 to 540 keV and in 800–900 keV has a focal length of 80 m. A multilayer telescope (ML), located in the hole left free by the NLL complements the lenses to extend the energy band down to $\sim 1$ keV.

Thicknesses can be further optimized to increase the lens sensitivity. Note that the LEL sensitivity can also be improved increasing its diameter. The exposure time is assumed to be $10^6$ s, while the band width is $\Delta E = E/2$. The detection efficiency is $\approx 1$.

In configuration 2, the expected HEL sensitivity to a 511 keV annihilation line of 3 keV FWHM, is $F_{\text{min}} \approx 4 \times 10^{-7}$ photons cm$^{-2}$ s$^{-1}$.

Figure 9. Expected 3$\sigma$ sensitivity for a $10^6$ s exposure time in the case of Configuration 1. The straight line shows the level of a 0.1 mCrab-like spectrum. A detection efficiency of $\approx 1$ is assumed.

Figure 10. Expected 3$\sigma$ sensitivity for a $10^6$ s exposure time in the case of Configuration 2. The straight line shows the level of a 0.1 mCrab-like spectrum. A detection efficiency of $\approx 1$ is assumed.

4. Conclusions

Laue lenses appear to be a promising approach in order to overcome significantly (even by 2 orders of magnitude, depending on energy) the sensitivity limitations of the current generation of direct-viewing telescopes, with or without coded masks. We have shown two examples of multi-lens configurations capable to cover the 60 to 600 keV band with unprecedented sensitivity.

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