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γ-Ray lenses – taking a deeper look at sites of nucleosynthesis

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Abstract

Focusing of γ-rays in the nuclear-line energy regime is a feasible and promising approach for high-sensitivity γ-ray (line) studies of individual sources. This approach combines two unique advantages over "traditional" instrumentation for γ-ray astronomy: arcminute resolutions and a decoupling of collection and detection areas, with the corresponding potential for increased sensitivity. Laue Lenses use diffraction on lattice planes in the volume of a crystal to concentrate photons. Suitable crystals for MeV lenses exist, and lenses with >100 keV bandpasses and ~arcmin fields-of-view are feasible today. Fresnel phase shift lenses present another, longer-term possibility for γ-ray focusing. The current status of instrumentation development, lens missions under consideration, and some of the nuclear astrophysics observations such instruments could enable are described.

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1. Introduction

One aim of γ-ray astronomy is to learn more about the sites of nucleosynthesis, namely massive stars, novae, and supernovae, by measuring γ-ray emissions from the decay of radioactive isotopes generated in the process of creating heavier elements. Only some of the predicted emission from such radioactive isotopes has been observed to date. One of the results from the Advanced Compton Telescope (ACT) study (Boggs et al., 2005) is the sensitivity requirement of several times 10^{-7} ph cm^{-2} s^{-1} for a systematic study of ^{56}Co emission from supernovae of type Ia. An energy band at least 50–100 keV wide is necessary to cover the SN line at 847 keV which is predicted to be broadened to ∼30 keV. Detailed comparisons between SN models are possible based on the time-evolution of the line flux; resolving the line profile would provide additional information and require an energy resolution on the order of 1%. Such sensitivity is hard to achieve in the background-intensive MeV regime, since increasing the detector area always incurs a corresponding increase in background that has to be subsequently suppressed.

There is one clear way out of this dilemma – decoupling the *instrument* effective area from the active *detector* volume, as is done at X-ray energies and below. Concentrating photons using a collecting area of several hundred cm^2 onto a few cm^2 detector surface area is possible at MeV energies – using Laue or Fresnel phase-shift γ-ray lenses.

2. Laue lenses

2.1. Laue diffraction – principles

Laue diffraction is the same as Bragg reflection – just at the crystal planes inside a crystal, as opposed to at its surface, allowing use of the full crystal volume instead of just its surface. Crystals with plane distances d small enough to fulfill the Bragg condition $2d\sin\theta = n\theta$ (n integer) for $\theta \approx 1°$ even at MeV energies do exist. By arranging such crystals in rings, photons from the area covered by the crystal ring can be concentrated onto a small detector surface area. However, if such a lens consisted of one ring of ideal monocrystals, it would have a bandpass of a few eV at most, rendering it virtually useless to the study objectives for e.g. the broad 847 keV line outlined above. In order both for the energy range (or angular range) covered to be of a reasonable width and for extinction in the diffraction crystal not to damp the desired diffracted radiation, the crystal used in such a Laue lens may not be a perfect single crystal. Instead, crystallites which are roughly, but not perfectly, aligned are desirable (Halloin, 2003). Such a crystal is called a *mosaic crystal*. Depending on the degree of misalignment of the crystallites, such a mosaic crystal can be a reasonably effective diffractor over a range of several keV. The energy range (or angular range) over which the mosaic crystal acts as an effective diffractor depends on the range of angles over which the crystallites are distributed. Mosaic crystals can reach diffraction efficiencies of ∼30% over bandpasses of several keV; temperature- or pressure-gradient as well as bent crystals are expected to be even more efficient.

2.2. Lens design and bandpasses

Building a Laue lens with a bandpass significantly larger than a few keV requires combining crystals at different lens radii (changing diffraction angles from a given crystal plane), using different crystal planes, and/or different crystals. The effective diffraction area of a lens at a given energy is of course directly dependent on the area the corresponding crystals can cover on the lens. While any crystal provides several plane spacings at different crystal orientations, in general the lowest-order orientations provide the highest diffraction efficiencies and are thus the most desirable – but they also correspond to the largest diffraction angles at a given energy. To cover large, continuous energy bands, crystals are arranged either in rings or in an Archimedes' spiral (see e.g. Frontera et al., 2005). To achieve reasonably large lens areas while only using high-efficiency crystal orientations, focal lengths on the order of 100 m are needed for observations at several hundred keV.

There is no fundamental limit to the lens size – increasing the lens scale by a factor s will increase the focal length by the same factor s, the collection area by a factor s^2 and the achievable point source sensitivity by a factor ∼s (Halloin, 2003). This estimate neglects the influence of the individual crystal's mosaicity, which results not only in the desired few-keV bandwidth per crystal, but also in a corresponding angular spread which translates to a somewhat extended focal spot on the detector. Increasing the lens-detector distance while keeping crystal parameters the same will therefore result in an increased focal spot size, partially negating the benefits of the larger lens if observations are not source dominated (see Figs. 1 and 2).

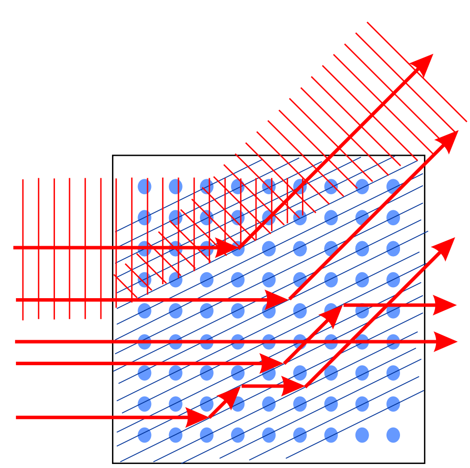

Fig. 1. Principle of Laue lenses – Laue diffraction in a perfect monocrystal.

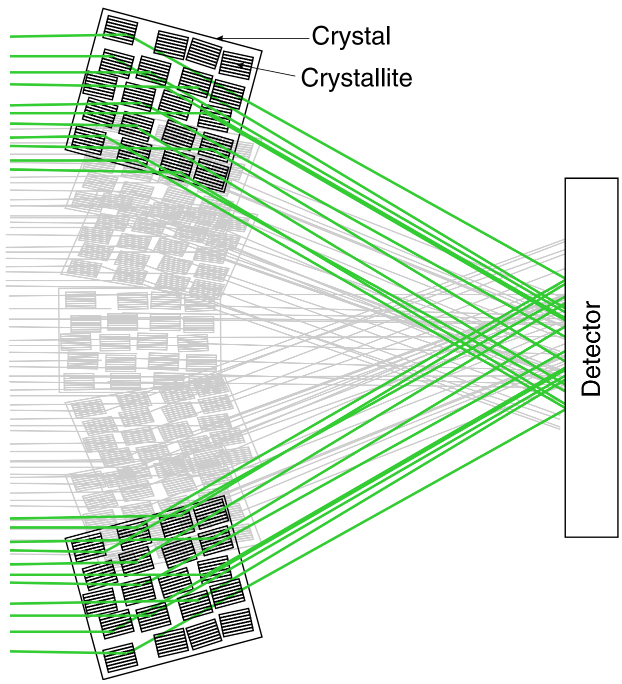

Fig. 2. Principle of Laue lenses – Laue diffraction in a mosaic crystal lens.

2.3. Photon collection vs imaging

Incidentally, such a Laue lens would also overcome a fundamental performance limitation of Compton Telescopes – the Doppler broadening which limits the achievable angular resolution to around 1° at 1 MeV (depending on the detector material's Z and the photon energy; Zoglauer et al., 2003). The lens would be collecting photons from a sky region a few arcmin across, with a PSF of less than 1 arcmin, increasing the angular resolution achievable by over an order of magnitude. Within the lens' field of view, source signatures on the detection plane differ depending on the incident direction. This enables sub-FoV source localization given a position-sensitive detection plane. Fig. 3 illustrates the focal-plane signatures of an 847 keV point source 0, 10, 20, and 30 arcsec off-axis on the detection plane of a multi-ring broad-bandpass Laue lens.

2.4. Balloon demonstration

In the astrophysical context, Laue lenses have first been suggested decades ago (Lindquist et al., 1968). Work by Ballmoos et al. (1995) and Smither et al. (1995) at CESR,

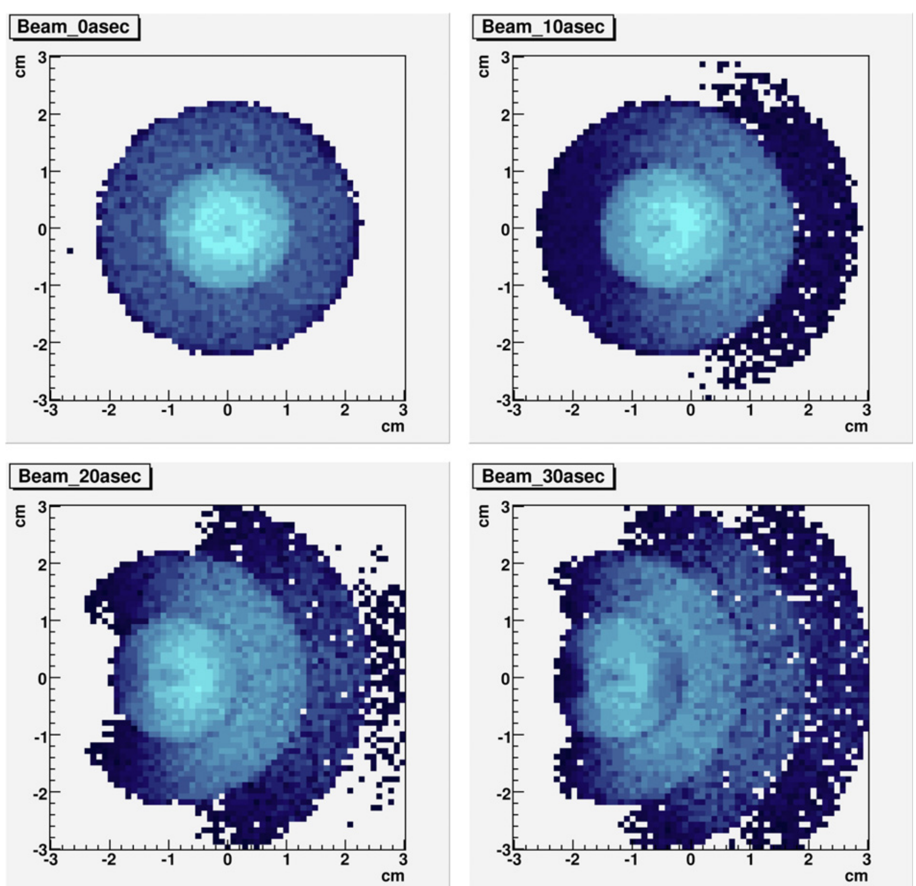

Fig. 3. Focal plane signatures of an 847 keV point source 0, 10, 20, and 30 arcsec off axis (logarithmic color scale), viewed through a multi-ring broad-bandpass Laue lens with focal length 86 m. Localization of strong point sources to 10–20 arcsec appears feasible with a finely pixellated focal plane. (based on Halloin, 2005).

Fig. 4. CLAIRE balloon lens consisting of eight sparsely-populated rings of Ge crystals.

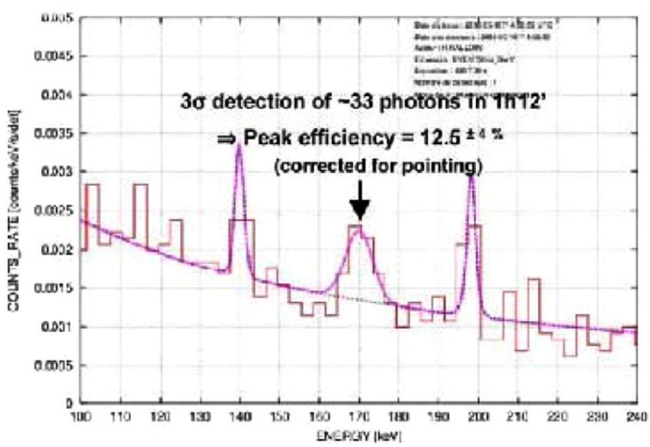

Fig. 5. CLAIRE balloon result: 32 photons from Crab were detected in ~1 h of balloon data in a narrow energy band (from Halloin et al., 2004).

Toulouse and Argonne resulted in a Laue lens composed of mosaic Ge crystals, called *CLAIRE* (see Fig. 4), which flew on a stratospheric balloon with Ge detectors at its focus to observe the Crab in 2001 (Halloin, 2003; Ballmoos et al., 2004a). *CLAIRE*'s lens consists of eight rings of Ge crystals, making use of different crystal planes and their respective spacings to obtain different diffraction angles for 170 keV photons and concentrate them on a focal spot 2.77 m from the lens over an energy band of ~3 keV. The detection of 33 ± 10 photons from Crab at 170 keV confirmed the proper function of this *mosaic* Laue lens (Halloin, 2003, see Fig. 5).

3. Fresnel phase-shift lenses

Fresnel Phase-Shift lenses for γ-ray astronomy have been suggested by Skinner (2001). They explore small deviations of the index of refraction from 1 at γ-ray energies. Fresnel lenses could enable diffraction-limited imaging in the γ-ray domain; sensitivities are predicted in the 10^{-9} ph cm^{-2} s^{-1} range for a focal length of 10^9 m. While these lenses are inherently optimized for a single photon energy, wider bandpasses can be achieved at the expense of angular resolution and/or effective area for a given narrow energy band. This concept has not yet been tested at MeV energies. The lens itself would be easy to manufacture – the challenges lie in the extremely long focal length which makes pointing the two-spacecraft telescope a true challenge and full ground testing impossible.

4. Focal plane instrumentation

4.1. Basic considerations

The detector of choice for any nuclear astrophysics mission should take maximum advantage of the information encoded in the astrophysical γ-ray lines, including any Doppler broadening or Doppler shifts of lines. Germanium detectors achieve the best energy resolution in the energy regime of primary interest (~100 keV to ~2 MeV) in detectors of reasonably large volumes.

A single, monolithic Ge detector at the lens' focus would of course be simplest. However, such a detector would have no means to distinguish between photons from the lens and background photons incident from other directions.

Simple segmentation of the detector into an "inner" and an "outer" zone would allow some background rejection without adding much complexity: only those photons would be accepted which interact at least once in the "inner" zone. Such zones could either be established via segmented contacts (fixed radius of the inner zone, unambiguous attribution of energy deposits to "inner" and "outer" zone even if a photon interacts more than once in the detector) or via pulse-shape analysis of the signals from a single-contact Ge monolith. The latter method would allow optimization of the diameter of the "inner" zone for each measurement, but at the price of localization ambiguities in the case of multiple interactions. Using segmented contacts would also slightly deteriorate the overall energy resolution for events scattering from the central to the outer zone (noise from two electronics channels affects the signal).

A Compton-detector focal plane would have several advantages:

- It would have a much better capability for background rejection, since each individual photon's origin can be determined to at least a circle on the sky. If this circle does not intersect the lens' position, the photon is rejected.
- It is inherently finely pixellated. This would also enable on-the-ground selection of source events according to current focal spot size and position. Moreover, only a detector with many pixels could hope to utilize a Laue lens' imaging (as opposed to merely concentrating) capability.
- It is inherently sensitive to γ-ray polarization.

These advantages come at the cost of a significant increase in the number of detector channels, with correspondingly higher demands on both instrument electronics and detector cooling. A Compton focal plane could also not be designed quite as compact as a single monolithic Ge detector, and supporting the much higher number of channels and correspondingly increased detector segmentation would necessitate more passive material within the detector assembly itself, increasing backgrounds.

4.2. Tradeoff study for different Ge designs

A tradeoff study of different Ge detector designs for a Laue lens focal plane has been initiated by Weidenspointner et al. (2006) and Wunderer et al. (2006b). Both the comparative performance of monolithic, segmented, and Compton focal planes, and the performance of different Compton focal plane designs are investigated. Each instrument is placed on a generic spacecraft and surrounded with plastic (top and sides) and BGO (bottom) anticoincidence shielding. The studies take into account the full instrumental background encountered by a satellite instrument in high-earth orbit or at L2 through Monte Carlo simulations using MGGPOD (Weidenspointner et al., 2005). Performance evaluation of the Compton telescopes leverages heavily off the toolset assembled for the ACT study (Boggs et al., 2005; Wunderer et al., 2006a and in particular Zoglauer et al. (2006)).

Compton designs outperform monolithic or segmented detectors in terms of γ-ray line sensitivities achievable; sensitivites of 1×10^{-6} ph cm^{-2} s^{-1} (10^6s, 3σ) can certainly be achieved for both the 511 keV line and a 3% FWHM broadened 847 keV line when using lenses with effective diffraction areas of ∼1000 cm^2. The estimates are conservative for reasons enumerated in Wunderer et al. (2006b). Sensitivities for narrow lines other than the positron-annihilation line at 511 keV are bound to be significantly better since the background level for this particular line is especially high.

5. Using lenses to study nucleosynthesis

A moderately-sized Laue lens in conjunction with a Ge focal plane could offer sensitive spectroscopy in 2–3 energy bands of particular relevance to nuclear astrophysics, with additional lower-efficiency capabilities at higher energies corresponding to the second (and third) order diffraction in the crystals. Any Laue-lens γ-ray spectrometer would have a field of view on the order of an arcminute, with limited imaging/point-source localization capabilities within that FoV. A Compton focal plane not completely surrounded by heavy shielding could provide secondary capabilities for all-sky monitoring at lower sensitivity levels. What could we accomplish with this?

Supernovae Ia, while considered ‘‘standard candles’’ for cosmology, are still not well understood. Observations of the shape and time-evolution of the 812 keV and 847 keV lines from ^{56}Co and ^{56}Ni would allow us to distinguish between competing explosion models. Fig. 6 illustrates the capability of a lens mission with 847 keV broad-line sensitivity of 1.0×10^{-6} ph cm^{-2} s^{-1} to distinguish between delayed-detonation and deflagration models for several supernovae in a mission lifetime.

Novae could be significant contributors of ^{7}Li; this could be confirmed by measuring 478 keV emission from decaying ^{7}Be from novae. The flux at maximum emission expected from a nova at 1 kpc is ∼1–2 × 10^{-6} ph cm^{-2} s^{-1}, with a line width on the order of 3–8 keV (Hernanz, 2006). A Laue mission achieving 1×10^{-6} ph cm^{-2} s^{-1} at 511 keV could be expected to achieve a narrow-line sensitivity of better than 5×10^{-7} ph cm^{-2} s^{-1} to the ^{7}Be line; this would translate to a sensitivity around 9×10^{-7} ph cm^{-2} s^{-1} to an 8 keV broadened line. Thus, a moderately-sized Laue lens should enable ^{7}Be decay detections for CO novae out to >1 kpc.

Of course, such an instrument would also enable astrophysical observations not related to decaying radionuclides: For example, detailed spectroscopy and mapping of 511 keV signatures from positron annihilation, e.g. in microquasar jets, would provide new insights, and observations in the fairly wide energy bands would provide powerful constraints on continuum emission. With a Compton detector focal plane, a Laue-lens mission would also provide γ-ray polarization measurements within the lens' energy bands.

The above-listed objectives constitute a subset of the goals of an Advanced Compton Telescope (Boggs et al., 2005), focusing on selected energy bands and observing one target at a time. A mid-sized γ-ray lens mission could provide a glimpse of some of ACT's most compelling science (see Fig. 7) and sub-arcminute angular resolution for observations of e.g. knots in supernova remnants.

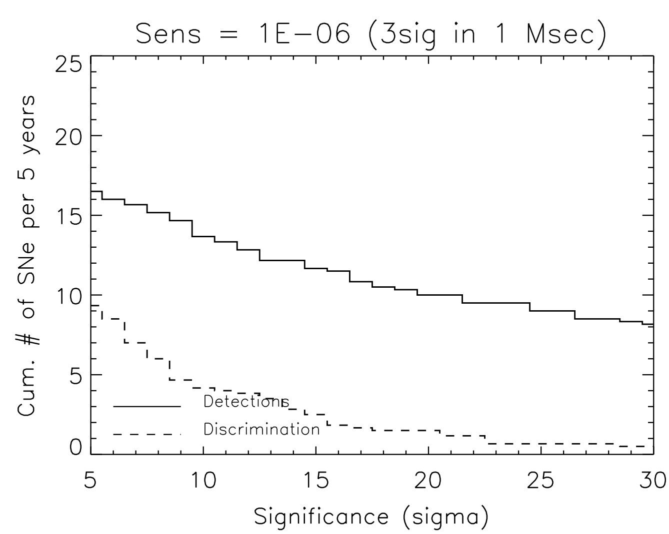

Fig. 6. SN Ia observations with a pointed γ-ray telescope achieving 1.0×10^{-6} ph cm^{-2} s^{-1} sensitivity to 3%-broadened 847 keV line emission. Both the expected number of SN Ia detections and the number of events for which discrimination between delayed-detonation (dd202c) and deflagration (W7) models would be possible during a 5-year mission are shown as a function of detection or discrimination significance. (Milne, 2005).

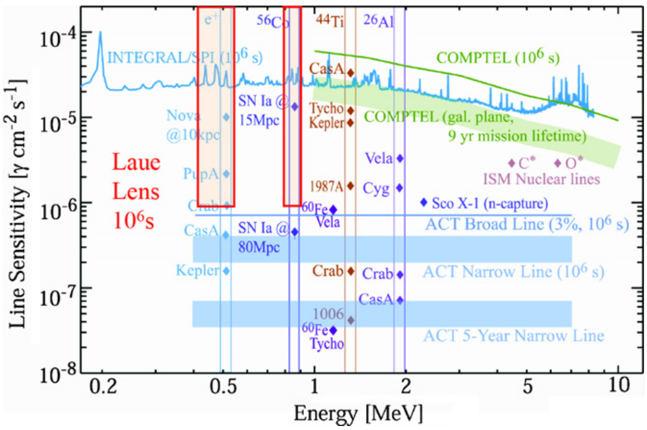

Fig. 7. A mid-sized γ-ray lens mission will provide a preview of some of ACT's most compelling science at sub-arcminute angular resolution.

An unshielded Compton detector focal plane would provide all-sky surveys at lower sensitivity levels than the lens-focal plane combination achieves for its narrow field of view, but with the same high spectral resolution. The resulting all-sky monitoring capability might also enable the instrument to detect its own ToOs, possibly including CO novae via their initial 511 keV flashes. This would be of particular interest for novae whose optical emission, which can also serve as ToO trigger, remains undetected.

6. Mission prospects

A mid-sized Laue lens for γ-ray astronomy, *MAX* (Ballmoos et al., 2004b), underwent a pre-Phase A study in France and continues to be funded. Cu and Ge crystals at ~100 m from the detection plane would provide several hundred cm^2 effective diffraction area at 450–530 keV and 800–920 keV. A third energy band or even larger lens effective areas are being considered. A *MAX*-like instrument would constitute an ideal science payload for a formation-flight pathfinder mission.

Also, a proposal to ESA for a larger Laue-lens based γ-ray mission is planned. For this instrument, a continuous energy band of 50 keV–2 MeV is envisioned (Knödlseder, 2005).

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