Gamma-ray Laue lenses under development for deep AGN observations

F. Frontera, E. Virgilli, V. Liccardo, V. Valsan
University of Ferrara, Physics Department, Via Saragat, 1, 44100 Ferrara, Italy
E-mail: frontera@fe.infn.it, virgilli@fe.infn.it, liccardo@fe.infn.it, valsan@fe.infn.it

V. Carassiti, F. Evangelisti, S. Squerzanti
INFN, Section of Ferrara, Via Saragat, 1, 44100 Ferrara, Italy
E-mail: carassiti@fe.infn.it, evangelisti@fe.infn.it, squerzanti@fe.infn.it

G. Risaliti
INAF, Astronomical Observatory of Arcetri, 50125 Firenze, Italy
E-mail: risaliti@arcetri.inaf.it

Abstract. We will review the status of the Laue lens development of space astrophysics and their importance for facing many open issues on AGNs.

1. Introduction
Broad band X-/low energy gamma–ray missions, like BeppoSAX, Rossi X–ray Time Explorer, INTEGRAL, have clearly shown that, in order to understand better the physics underlying several classes of Galactic and extragalactic sources, two main requirements on the instrumentation are crucial: a) to cover a broad energy band (from a fraction of keV to several hundred keV); b) to achieve a high spectrum sensitivity on time scales at least shorter than the source flux variability time scales.

To meet both requirements, it is crucial to use focusing telescopes. The current experimental scenario is the following: a) low energy X–ray (0.1-10 keV) telescopes are available and are well tested in space; b) medium energy X–ray (up to 70/80 keV) telescopes, based on multilayer mirrors, are mature and will be tested in space in the next future (American ‘NUSTAR’ mission, Japanese ’ASTRO–H’ mission); c) high energy X–ray (>70/100 keV) telescopes are under development.

But, why extend the band to energies higher then 70/80 keV? For a review of the science goals at high energies, see, e.g., Ref. [1]. Here we shortly discuss some open issues on Active Galactic Nuclei (AGNs), that could be settled with broad band observations that cover the 511 keV annihilation line.
1.1. Radio Quiet (RQ) AGNs for cosmology

Many open issues still exist about this class of sources (mainly type 1 and 2 Seyfert). Extremely important is to establish the contribution of this class of source to the cosmic X–ray background. Issues that are still not clear include the relative size of unabsorbed ($\log N_H < 21.5$), Compton–thin ($21.5 < \log N_H < 24.5$) and Compton-thick ($\log N_H > 25$) RQ AGNs, the luminosity function and evolution of each of the above populations with energy, the distribution of high energy cutoff ($E_F$) of each population.

Currently, in the synthesis models of the Cosmic X–ray Background (CXB) [2], it is assumed a combination of unobscured, Compton thin and Compton thick RQ-AGN populations with assumptions about the size of each sub–population, a scatter in the photon index power–law spectrum with a high energy cutoff $E_F$ kept fixed (see Fig. 1). Are the assumption parameters right? Is it right to assume a fixed $E_F$? On the basis of the INTEGRAL results recently reported by Ref. [3], in the local Universe, this does not seem to be the case (see Fig. 1).

Soft gamma–ray observations ($> 100$ keV) of unprecedented sensitivity such as those possible with focusing optics, can test and improve the synthesis models.

1.2. Radio Loud (RL) AGN physics and their contribution to hard CXB

In the case of RL–AGNs (Blazars), it is well known that they show two humps in their Spectral Energy Distribution (SED) (e.g., Ref. [4]), one interpreted as synchrotron emission, the other as Inverse Compton. As can be also seen from Fig. 2, it is found that the photon peak energy of the second hump decreases with the luminosity increase, with low luminosity sources identified with BL Lacs and high luminosity sources with Flat Spectrum Radio Quasars (FSRQ). For the brightest sources the second hump is just around 400 keV, while, around this photon energy, the less luminous have their spectral dip between first and second hump. This means that the most powerful and distant blazars can be more easily picked up through sensitive soft gamma–ray observations, that become crucial to test the emission models of RL–AGNs. The soft gamma–ray
Figure 2. Luminosity distribution of blazars, also called blazar sequency. Solid lines are the phenomenological SED. The data are the SED of real sources detected in the first 3 months of survey by the Fermi satellite (LBAS catalog: Abdo et al. 2009), divided (different colors) into bins of different-ray luminosities in the 0.110 GeV energy band: \( \log L < 45.5 \) (blue), \( 45.5 < \log L < 46.5 \) (green) \( 46.5 < \log L < 47.5 \) (red), \( \log L > 48.5 \) (black). Reprinted from Ref. [4].

The band between 100 and 600 keV is also important to evaluate the contribution of RL–AGN to the hard X–ray CXB, an issue recently faced by Ref. [5] using the 25–55 keV spectral data obtained with the Swift BAT instrument and thus by extrapolating to higher energies the observed and derived (e.g., X–ray luminosity function) properties at low energies.

To perform studies of these sources beyond 100 keV energies, focusing telescopes are needed.

1.3. Polarization of the gamma–ray emission from AGNs
In spite of its importance to establish the emission physics, the polarization level of the X–/gamma–ray emission from celestial X–sources is a still open issue. The only source, for which polarization measurement positive results are reported, is the Crab Nebula [6, 7]. Recently with INTEGRAL a highly polarized signal (polarization fraction of \( 67 \pm 30\% \)) has been discovered in the soft gamma–ray emission (> 400 keV) from Cygnus X–1 [8]. This discovery opens a new window in the gamma–ray astronomy, showing that with more sensitive instruments the observation of polarized emission could be detected even from extragalactic sources, like RL–AGNs, from which polarized emission is predicted but never observed.

1.4. Dark matter in Galaxies
Positron production can occur in a variety of cosmic explosions and acceleration sites. It is expected to be the result of the presence of antimatter but it is also expected in the case of dark matter (see, e.g., Ref [9]). Thus the observation of the characteristic 511 keV annihilation line provides a powerful tool to probe the nature of dark matter. The found evidence of a diffuse annihilation line emission from the Galactic Center region with INTEGRAL [10] has also been interpreted as due to collisionally excited dark matter, that de-excites by \( e^+e^- \) pair emission [11]. In order to confirm the INTEGRAL results, to establish the diffuse or discrete distribution of the annihilation radiation, and possibly to extend the search of annihilation line to external galaxies and AGNs, much more sensitivity is needed, only achievable with focusing gamma–ray
2. Requirements for soft gamma–ray focusing telescopes

The requirements for hard X–/soft gamma–ray focusing telescopes can be summarized as follows:

a) Broad bandpass (at least 80/100–600 keV); b) Continuum sensitivity 2 orders of magnitude better than the current instrumentation, like the ISGRI instrument aboard the INTEGRAL satellite, with a design goal of $10^{-8} \text{ ph/(cm}^2\text{s keV)}$ in a bandwidth $\Delta E = E/2$ for an observation time $T = 10^5$ s; c) Imaging capability, with angular resolution better than 1 arcmin (design goal 20 arcsec). We propose as focusing instrument in the soft gamma–ray band a Laue lens (for an exhaustive review, see Ref. [1]).

3. Laue lens principle

Laue lenses use the interference between the periodic nature of the electromagnetic radiation and a periodic structure such as the matter in a crystal. In a Laue lens, the photons pass through the full crystal, using its entire volume for interacting coherently. In order to be diffracted, an incoming gamma–ray must satisfy the Bragg condition:

$$2d_{hkl} \sin \theta_B = n \frac{hc}{E}$$  \hspace{1cm} (1)

where $d_{hkl}$ (in Å) is the spacing of the lattice planes $(hkl)$, $n$ is the diffraction order, $hc = 12.4 \text{ keV Å}$ and $E$ is the energy (in keV) of the gamma-ray photon.

A Laue lens for astrophysical applications is made of a large number of crystals, that are disposed in such a way they will concentrate the incident radiation onto a common focal spot. A convenient way to visualize the geometry of a crystal lens is to consider it as a spherical cup covered with crystal tiles having their diffracting planes perpendicular to the sphere (see Fig. 3). The focal spot is on the symmetry axis at a distance $f = R/2$ from the cup, with $R$ being the radius of the sphere of which the spherical cup is a part; $f$ is the lens focal length.

The main requirement for the disposition of the crystals in the lens is to get a smooth dependence of the lens effective on photon energy. This result is achieved using ring-like configurations for long focal lengths ($> 20$ m) and spiral-like configurations for smaller ones.

4. Crystals for Laue lenses

Different crystal materials are suitable to be used for Laue lenses. Among them, we mention Silicon, Copper, Germanium, GaAs, Gold, etc. Two crystal structures are suitable, mosaic...
Figure 4. Left panel: 3σ Sensitivity of a 20 m focal length Laue lens made of flat mosaic crystal tiles of Cu(111) with 30 arcsec mosaicity and 70–300 keV nominal energy passband, compared with the corresponding lens in the case that the crystals are properly curved. The time measurement assumed is $10^5$ s, while the energy bins have an amplitude $\Delta E = E/2$.

Right panel: Difference between the PSF measured and that obtained with a Monte Carlo code by assuming a perfect positioning of the crystal tiles in the lens. Reprinted from Ref. [12].

- Mosaic crystals
  Mosaic crystals are made of misaligned perfect microcrystals, with misalignment distribution well described by a Gaussian function. The FWHM of the Gaussian is the crystal mosaicity.

- Curved crystals
  Curved crystals have important advantages with respect to mosaic crystals: a) No limit to their diffraction efficiency, while for mosaic crystals the maximum theoretical value of the diffraction efficiency is 0.5; b) Better lens focusing for a proper crystal curvature.

It is found that for the same focal length, the angular resolution of a lens made of curved crystals significantly improves. As an example, for 20 m focal length, the angular resolution increases from 3.5 arcmin to 20 arcsec, with the source image area that decreases by a factor about 100. As a consequence, also the lens sensitivity increases with respect to flat mosaic crystals. As an example, in Fig. 4, left panel, we compare the sensitivity of a 20 m focal length Laue lens made of curved crystals of Cu(111) with 30 arcsec mosaicity with that made of flat mosaic crystals tiles (size 15×15 mm²) of the same material and mosaicity. To achieve the design goal of $10^{-8}$ ph/(cm² s keV) in $10^5$ s of observation time, in addition to the use of bent crystals, that allow the narrowest PSF and the background level minimization, in the same lens more crystal materials have to be used, each optimized in the energy band where it shows its highest reflectivity.

Techniques to curve crystals have already been developed. There are different production methods to get curved crystals, among which the indentation of one of the two wafer faces. The last technique has been developed at the University of Ferrara with very satisfactory results for Silicon and Germanium.

5. Lens assembly technology development

At the University of Ferrara we have already developed a crystal assembling technology suitable for building lenses with moderately short $(\leq 10–15 \text{ m})$ focal lengths. Using this technology, a first lens prototype with 6 m focal length has already been developed and tested. It makes use of flat mosaic crystals of Cu(111). The first light of the first prototype is shown in Fig. 4,
right panel, where the black field region is the expected image size. The corona still visible in this image is the result of the cumulative errors done during the lens assembly process. A new prototype is being developed that takes into account the experience gained from the first one.

For longer focal length lenses, new crystal assembly technologies are needed. To this end, a new project, "LAUE", supported by Italian space agency ASI, has been started with the contribution of the Italian industry. A lens petal made of curved crystals with 20 m focal length is being developed and an accommodation study of a lens made of petals for a satellite mission is being performed.

6. Conclusions

The hard X–/gamma–ray band covered by Laue lenses is crucial for high energy astrophysics. Given their much higher expected sensitivity (two orders of magnitude better than the current instrumentation), Laue lenses can face key importance astrophysical issues still open on AGNs.

A big effort is now in progress for the development of focusing Laue lenses. The development of curved crystals improves sensitivity and angular resolution by about an order of magnitude with respect to Laue lenses with mosaic crystals. A project "LAUE", supported by the Italian space agency ASI, is on going with production also of the curved crystals. We do not expect to need high focal lengths (>20 m) for extending the band up to 600 keV, while an energy passband up to 300 keV can be easily obtained with 10 m focal length. Thus the possibility of a broad band (1-600 keV) satellite mission with both multilayer mirrors and Laue lenses is becoming a firm perspective.

Acknowledgments

The lens development is the result of a big effort of several people. We wish to thank all of them. We wish to thank the significant efforts by DTM in Modena, Thales–Alenia Space, Italy in Milan and Turin, CNR/IMEM Institute in Parma, INAF/IASF in Bologna, Sensor and Semoconductor Laboratory (LSS) of the University of Ferrara. In addition we wish to thank all the other members of the Ferrara team interested to this development. We acknowledge the support of ASI, that has permitted the past and present activity in this field.

References

[1] Frontera F and Von Ballmoos P 2010 X–ray Optics and Instrumentation 2010 100740 (Preprint 1007.4308)
[2] Gilli R, Comastri A and Hasinger G 2007 Astronomy and Astrophysics 463 79–96
[3] Molina M, Bassani L, Malizia A, Stephen J B, Bird A J, Dean A J, Panessa F, de Rosa A and Landi R 2009 Monthly Notices of the Royal Astronomical Society 399 1293–1306 (Preprint 0906.2909)
[4] Ghisellini G 2011 ArXiv e-prints (Preprint 1104.0006)
[5] Ajello M, Costamante L, Sambunara R M, Gehrels N, Chiab J, Rau A, Escale A, Greiner J, Tueller J, Wall J V and Mushotzky R F 2009 The Astrophysical Journal 699 603–625
[6] Weisskopf M C, Silver E H, Kestenbaum H L, Long K S and Novick R 1978 The Astrophysical Journal Letters 220 L17–L121
[7] Dean A J, Clark D J, Stephen J B, McBride V A, Bassani L, Bazzano A, Bird A J, Hill A B, Shaw S E and Ubertini P 2008 Science 321 118–3
[8] Laurent P, Rodriguez J, Wilms J, Cadolle Bel M, Pottschmidt K and Grinberg V 2011 Science 332 438– (Preprint 1104.4282)
[9] Arkani-Hamed N, Finkbeiner D P, Slattery T R and Weiner N 2009 Physical Review D 79 015014– (Preprint 0810.0713)
[10] Weidenspointner G, Skinner G, Jean P, Knödlseder J, von Ballmoos P, Bignami G, Diehl R, Strong A W, Courdel B, Schanne S and Winkler C 2008 Nature 451 159–162
[11] Finkbeiner D P and Weiner N 2007 Physical Review D 76 083519– (Preprint arXiv:astro-ph/0702587)
[12] Frontera F, Loffredo G, Pisa A, Nobili F, Carassiti V, Evangelisti F, Landi L, Squerciati S, Caroli E, Stephen J B, Andersen K H, Courtois P, Auricchio N, Milani L and Negri B 2008 Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series (Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series vol 7011)