IL NUOVO CIMENTO VOL. 20 C, N. 5 Settembre-Ottobre 1997

Bragg concentrators for hard (> 10 keV) X-ray astronomy: Status report(*)

G. PARESCHI(1)(**), F. FRONTERA(1)(2) and G. PASQUALINI(1)

(1) *Dipartimento di Fisica, Università di Ferrara - 44100 Ferrara, Italy*
(2) *Istituto di TESRE/CNR - 40129 Bologna, Italy*

(ricevuto il 4 Aprile 1996; approvato il 24 Maggio 1996)

Summary. — The use of focusing telescopes in hard X-ray ($E > 10$ keV) astronomy will provide better flux sensitivity and imaging perfomances with respect to the direct-viewing detectors, utilized until now. We present recent results obtained from our group regarding the possible use of Bragg-diffraction technique to design hard X-ray focusing telescopes.

PACS 96.40 – Cosmic rays.
PACS 95.55 – Astronomical and space-research instrumentation.
PACS 95.85 – Astronomical observations.
PACS 98.85.Nv – X-ray.
PACS 01.30.Cc – Conference proceedings.

1. – Introduction

The flux sensitivity of direct-viewing detectors in X-ray astronomy is strongly limited by the Poissonian noise, that increases with the detector surface. The only pratical way to overcome this problem is to focus the X-rays collected from a large passive area, onto a small-area detector. Focusing optics will also provide better imaging performances than detectors with masks.

For this reason, low-energy telescopes with focusing optics based on the phenomenon of total external reflection, has allowed to achieve much higher flux and angular resolution sensitivities in the classical X-ray band ($E < 10$ keV) [1].

Unfortunately, in the hard-X-ray band ($E > 10$ keV), where the critical grazing reflection angles are extremely small and, consequently, the allowed collecting areas are very limited, this technique becomes inefficient.

(*) Paper presented at the VII Cosmic Physics National Conference, Rimini, October 26-28, 1994.
(**) Current address: Danish Space Research Institute, Juliane Maries Vej 30, DK-2100 Copenhagen, Denmark.

TABLE I. – *HAXTEL Configuration.*

Number of concentrator mirrors	28
Mirror height h (cm)	60
Top radius of the outer mirror (cm)	134
Top radius of the inner mirror (cm)	10
Focal length FL (cm)	380
Mirror mechanical support material	nickel
Mirror support thickness (mm)	1
Nominal operation band (keV)	10–140
Effective area at 15 keV (cm^2)	1000
Effective area at 60 keV (cm^2)	100
Effective area at 100 keV (cm^2)	35
Sensitivity at 15 keV (10^{-6} Crab and $T_{\mathrm{int}} = 10^5$ s)	8
Sensitivity at 60 keV (10^{-6} Crab and $T_{\mathrm{int}} = 10^5$ s)	190
Sensitivity at 100 keV (10^{-6} Crab and $T_{\mathrm{int}} = 10^5$ s)	670

Several alternative concentration techniques have been recently proposed aiming at the development of focusing optics in the high-energy X-ray band [2]; among them, the use of multiple small-angle reflection in the interior of glass microcapillars and multichannel plates, the reflection from continuously graded multilayers and the Bragg diffraction from mosaic crystals are particularly promising. In what follows we report on more recent results regarding the latter technique currently under study in our group.

2. – HAXTEL: a telescope concept based on mosaic crystal diffraction

Mosaic crystals can be described as a set of a large number of crystallites of microscopical or submicroscopical size, which are oriented almost, but not exactly, parallel to each other. While the diffraction from each crystallite is coherent, there is no coherence between photons scattered from different blocks. The misalignement distribution of microblocks lattice planes with respect to the mean orientation (mosaic spread) is, with good approximation, a Gaussian function.

With respect to a perfect crystal, which achieves high reflectivity in a narrow angular range centered in the Bragg peak, a mosaic crystal maintains a significant reflection power over a much larger angular range, depending on the mosaic spread.

The idea to utilize Bragg diffraction technique (in reflection geometry) from mosaic crystals to focus celestial hard X-rays with continuous photon spectra is described in several previous publications [3-6]. The proposed telescope consists of a set of confocal paraboloidal mirrors. The mirror positions satisfy the following criterion: top radius of a given mirror is equal to the bottom radius of the adjacent outer mirror. Each mirror support is covered by many pieces of mosaic crystals with average reflecting planes parallel to the crystal surfaces. All the mirrors have the same height. With this geometrical construction it is possible to concentrate polychromatic photons into a small focal plain detector. An important feature of Bragg telescopes is the strong dependence on the minimum threshold energy.

Results of a study by De Chiara and Frontera [3], devoted to optimize the parameters of such a kind of optics, have shown that pyrolytic graphite (002) is much suitable as reflecting material with the following mosaic parameters: crystal thickness of 2 mm, microblock thickness of about 100 times the lattice spacing d_{002} of graphite (d_{002}=3.354 Å) and mosaic spread of 0.2°, that is a good compromise between large integrated reflectivity and small defocusing of photons on the focal plane due to crystallites misalignement.

In table I we summarize the parameters of HAXTEL (HArd X-ray TELescope), a concept of a medium-size telescope configuration based on the geometrical construction described above. In table I we give also the values of the effective area and flux sensitivity at three different energies with an integration time of 10^5 s.

3. – Recent results

In what follows we will review some properties of graphite Bragg concentrators we have recently studied.

3˙1. *Intrinsic polarimetric capability.* – The reflectivity of a mosaic crystal (and consequently the telescope effective area A_{e}) depends on the polarization angle ϕ between the electric field of incoming X-ray photons and the plane of reflection. De Chiara and Frontera [3] reported the expression of the reflectivity R as a function of the photon energy E, glancing incidence angle θ and polarisation angle ϕ.

Exploiting this property of mosaic crystals, Bragg concentrators have an intrinsic capability to detect polarization from astrophysical objects. Indeed the intensity of reflected polarized photons in the focal plane results to be azimuth modulated: different angular sectors of the photon distribution in the focal plane show different intensity [3, 7]. Figure 1 shows the dependence of the percentage effective area on ϕ for the telescope configuration described in table I in the case of polarized photons with energy 10.8 keV, 21 keV and 28 keV. For this purpose we used the reflectivity expression for mosaic crystals given in [3] as a function of the polarization angle of incoming photons. We have obtained similar results also with Monte Carlo simulations we have performed [7], in which we adopted the model of Sanchez del Rio and coworkers to describe the misalignement of normals to cristallites with respect the normal to the mean reflection plan [8].

The expected performance of the telescope as a polarimeter was also evaluated. The Minimum Detectable Polarization (MDP) with 99% of confidence level is shown in table II for three different energy bands, three different source flux and an integration time of 10^5 s [7]. For this evaluation we assumed celestial X-ray sources with a Crab-like spectrum ($I(E) = k \times E^{-2.1}$ photons/(cm^2 s keV)).

3˙2. *Imaging capability and field of view.* – We recently reported the imaging capabilities of Bragg telescopes [6]. In order to investigate the angular resolving power, a Monte Carlo code that simulates beams of parallel X-ray photons incident on the telescope top has been utilized. The code was previously described [5].

TABLE II. – *Minimum Detectable Polarization* (%).

Energy band (keV)	Incident flux (mCrab)		
	1000	100	10
10–20	2.6	8.5	26.6
20–30	8	26	83
30–40	31	98	–

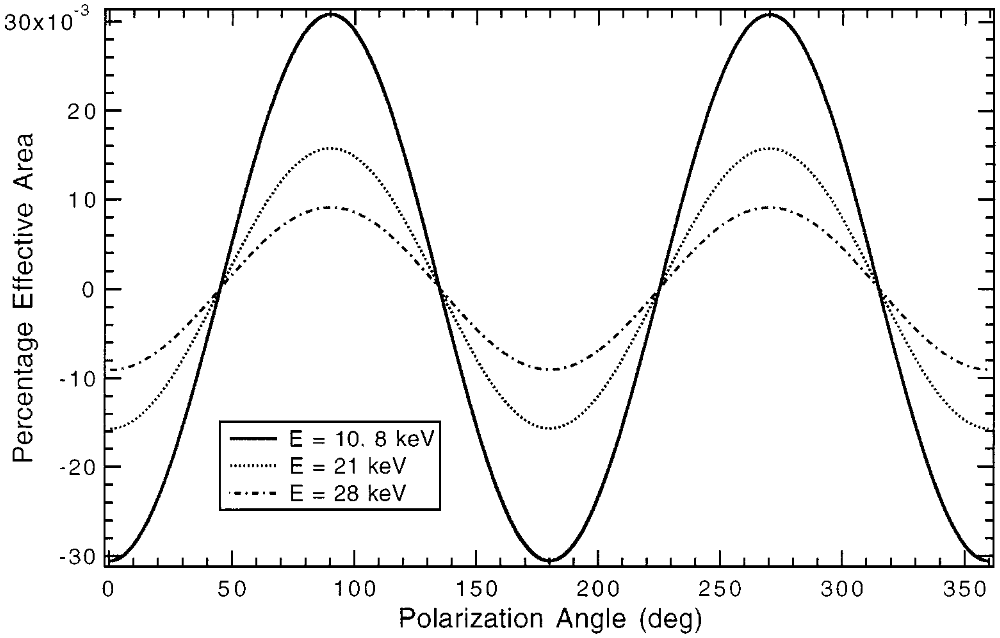

Fig. 1. – Percentage effective area as a function of polarization angle ϕ at three different energies for HAXTEL; as can be seen, the modulation amplitude decreases with the photon energy (taken from [7]).

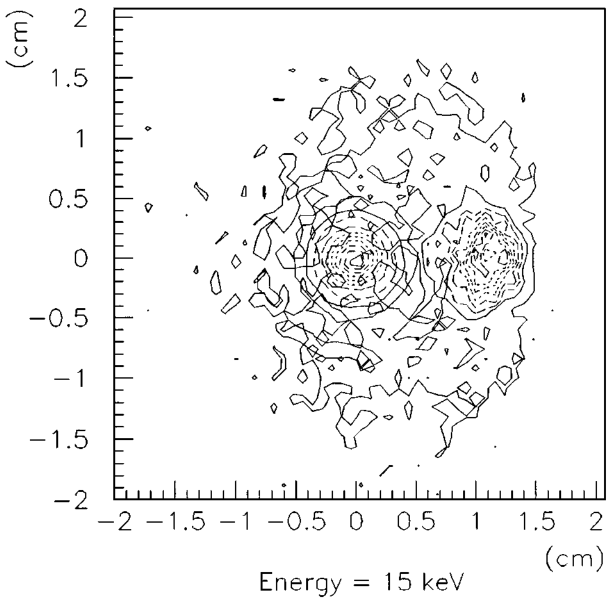

Fig. 2. – Contour plot of the 15 keV light distribution on the detector plane due to two sources, one on-axis and one 10 arcmin apart, for a 380 cm focal length Bragg telescope (taken from [6]).

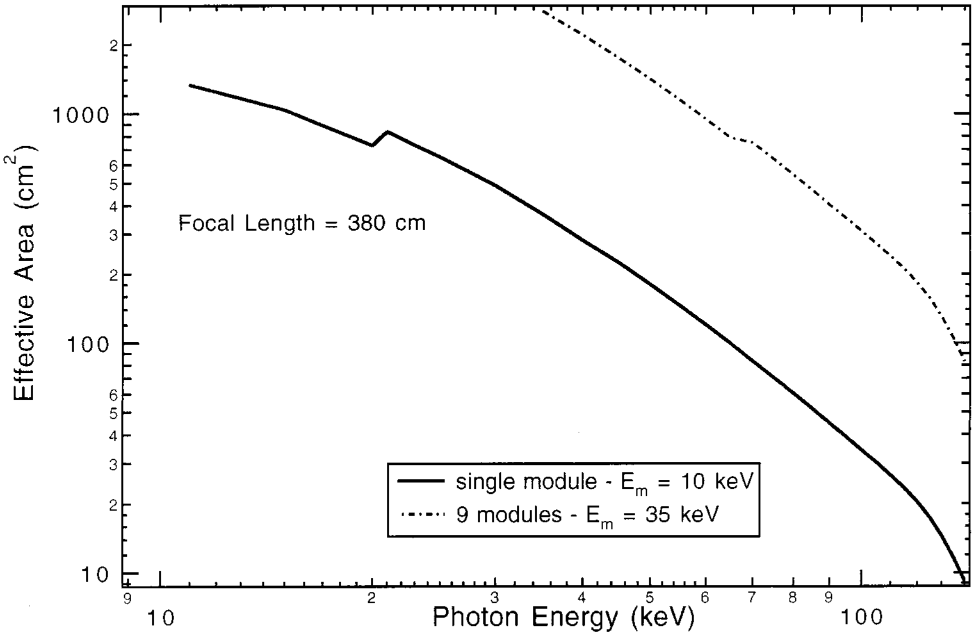

Fig. 3. – Effective area for a 380 cm focal length Bragg telescope with a minimum operative energy $E_{\rm m}$=10 keV and for a set of 9 modules with $E_{\rm m}$=35 keV allocated in a room of equivalent area (see also fig. 4).

As a result of such a study, we found that light distribution of photons in the focal plane cannot be fitted with a Gaussian, even though it shows a sharp peak with a full width at half-maximum (FWHM) that depends on photon energy. For the telescope configuration of table I the FWHM corresponds to an angular resolution of about 4 arcmin at 15 keV and 1.5 arcmin at 80 keV. The field of view results to be about 40 arcmin (FWHM) with off-axis images affected by aberration defects (coma). In fig. 2 we show the light distributions of two sources separated by 10 arcmin at 15 keV; as one can observe, the two sources are clearly resolved.

It is worthy to note that a position-sensitive detector, with good properties of spatial resolution (less of 1 mm) is needed to exploit the imaging properties of Bragg telescopes. Still better resolution (0.5 mm) is requested if we want to use the concentrators as polarimeters, to allow the study of the azimutal distribution of reflected photons in the focal plane.

For this reason a detector with the requested characteristics based on Germanium strips could be a good solution. Also Mercuric Iodide cameras, as recently proposed by Dusi *et al.* [9], appear of great interest.

3˙3. *Design optimization criteria.* – A drawback of the telescope configuration described in table I is its large diameter (268 cm). For that, we have studied possible ways to decrease the dimensions of such kinds of telescopes [6, 10]. In fact, as mentioned above, in a Bragg telescope the dimensions depends strongly on the minimum reflection energy

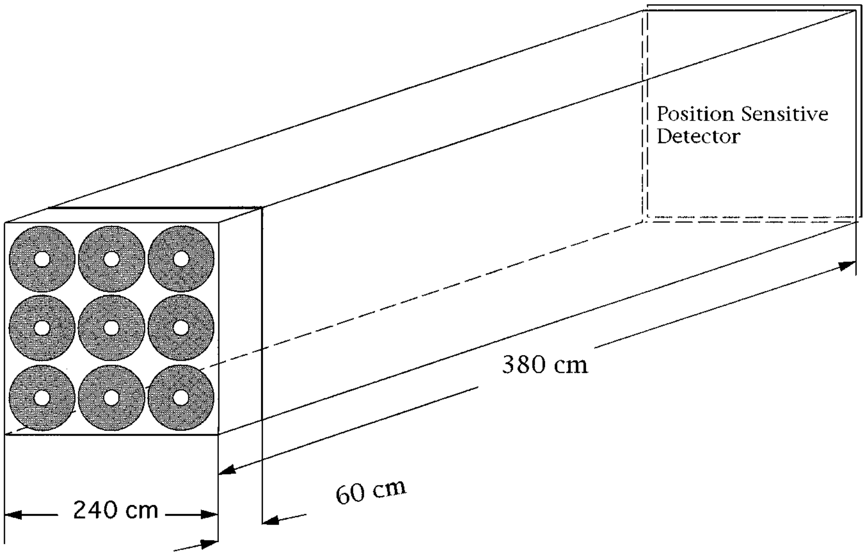

Fig. 4. – A 380 cm focal length multimodular telescope configuration. The minimum operative energy E_m of each module is 35 keV. The set of 9 modules is allocated in the same room needed by a same focal length telescope but with $E_\mathrm{m}=10$ keV.

E_m. In particular, the external diameter D decreases according to the following law:

$$D(E_\mathrm{m}) = D_{10\,\mathrm{keV}} \times \left(\frac{E_\mathrm{m}}{10\,\mathrm{keV}}\right)^{-1}, \tag{1}$$

where $D_{10\,\mathrm{keV}}$ is the external diameter of a telescope at $E_\mathrm{m}=10$ keV. In the case of a 380 cm focal length telescope (HAXTEL), the diameter diminishes from 268 cm when $E_\mathrm{m} = 10$ keV (see table I) to 80 cm when, *e.g.*, $E_\mathrm{m} = 35$ keV. Thus, if the telescope diameter must be kept within given values, the only solution is to rise the minimum operative energy of the telescope. Alternatively, the room needed by a telescope with a energy threshold of 10 keV, can be used to allocate a set of 9 modules with a diameter of 80 cm and $E_\mathrm{m}=35$ keV, with a sensitive increase of the effective area at high energies (see fig. 3). A schematic view of this telescope configuration is shown in fig. 4.

4. – Discussion and conclusion

As a result of the properties above studied, the Bragg diffraction from mosaic crystals is a good candidate technique for the construction of a focusing telescope with an operative range up to about 200 keV. We have shown the good imaging capability of the Bragg concentrators, in addition to a field of view that can be of particular interest for sky surveys. Another important characteristic of Bragg telescopes is the capability to detect the polarization of incoming photons.

A feature of these telescopes is their diameter that strongly decreases with energy: large diameter values are needed for a minimum operative energy of 10 keV. At this energy, telescopes based on multilayers appear more compact [10]. Thus a possible payload for a future wide-band X-ray astronomy mission could be based on a combination of mosaic crystal concentrators devoted to higher-energy photons (*e.g.*, $E_{\mathrm{m}} > 35$ keV) with telescopes based on one of the other techniques described by Gorestein [2] (microcapillars, multichannel plate optics, multilayers) that appear more suitable to focus lower-energy photons. For this aim, the use of Wolter I multilayer telescopes, recently proposed [11], is of particular interest.

* * *

This research is supported by the Italian Space Agency ASI, Ministero Università e Ricerca Scientifica e Tecnologica and Consiglio Nazionale Ricerche of Italy.

REFERENCES

[1] BRADT H. V. D., OHASHI T. and POUNDS K. A., *X-ray astronomy missions, Annu. Rev. Astron. Astrophys.*, **30** (1992) 391.

[2] GORESTEIN P., *Non-traditional grazing incidence optics for X-ray astronomy, Proc. SPIE*, **1546** (1991) 91.

[3] DE CHIARA P. and FRONTERA F., *Bragg diffraction technique for concentration of hard X-rays for space astronomy, Appl. Opt.*, **31** (1992) 1361.

[4] FRONTERA F., DE CHIARA P., GAMBACCINI M., LANDINI G. and PASQUALINI G., *Hard X-ray imaging via crystal diffraction: the first results of reflectivity measurements, Proc. SPIE*, **1549** (1991) 113.

[5] PASQUALINI G., DE CHIARA P. and FRONTERA F., *Development status of Bragg hard X-ray concentrators for space astronomy, Nuovo Cimento C*, **15** (1992) 879.

[6] FRONTERA F. and PARESCHI G., *Hard X-ray imaging via focusing optics with mosaic crystals, Exp. Astron.*, **6** (1995) 25.

[7] FRONTERA F., DE CHIARA P., PARESCHI G. and PASQUALINI G., *Polarimetric performance of a Bragg hard X-ray (> 10 keV) concentrator, Proc. SPIE*, **2283** (1994) 85.

[8] SANCHEZ DEL RIO M., BERNSTORFF S., SAVOIA A. and CERRINA F., *A conceptual model for ray tracing calculations with mosaic crystals, Rev. Sci. Instrum.*, **63** (1992) 932.

[9] DUSI W., CAROLI E., DI COCCO G., DONATI A., RAMUNNO G., GRASSI D. and PERILLO E., *A mercuric iodide X-ray camera for high energy astronomy, Proceedings of the Capri Workshop on Imaging in High Energy Astronomy*, edited by L. BASSANI and G. DI COCCO (Kluwer Academic Publisher, Dordrecht) 1995, p. 351.

[10] FRONTERA F. and PARESCHI G., *Comparative study of hard (>10 keV) focusing techniques for space astronomy, Proc. SPIE*, **2515** (1995) 2.

[11] CITTERIO O., FRONTERA F., JOENSEN K., GORENSTEIN P. and PARESCHI G., *New conception multilayer hard X-ray telescope for X-ray astronomy, Proceedings of the Capri Workshop on Imaging in High Energy Astronomy*, edited by L. BASSANI and G. DI COCCO (Kluwer Academic Publisher, Dordrecht) 1995, p. 259.