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Hard X-ray polarimetry using scintillators (*)(**)

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Summary. — The linear polarization of the radiation from celestial sources can be investigated by studying the angular distribution of Compton scattered photons in a detection device. In this contribution we present the design of a Compton polarimeter based on the technology of fiber-shaped scintillators. A total geometric area of 1000 cm^2 or more could be obtained by repeating a basic polarimeter composed by several fiber-like scintillators, some of them of low Z, acting as active scatterers, and others of high Z, acting as detectors. Polarimetric measurements can thus be carried out by searching for coincidences between a scatterer fiber and an absorber one. Monte Carlo simulations of the performances of such a device, when employed onboard a stratospheric balloon, are compared with other kinds of X-ray polarimeters.

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1. – Introduction

The importance of polarimetric studies in X-ray astronomy has been extensively pointed out by several authors (see, *e.g.*, [1]). Since the beginning of X-ray astronomy, only one polarimeter has successfully flown, onboard the OSO-8 mission [2]. The most important result obtained by this instrument (the measurement of the 19% linear polarization from the Crab Nebula at 2.6 and 5.2 keV) has highlighted the importance of this kind of measurements. The only polarimeter presently scheduled to fly onboard a satellite (the Russian mission Spectrum-X-Γ) is the US/Italian *Stellar X-Ray Polarimeter* (SXRP), which will fly by the end of 1998. This polarimeter operated at the focus of the grazing incidence telescope SODART and will be able to measure the linear polarization of cosmic sources at 2.6 and 5.2 keV (by the Bragg stage) and

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between 5 and 15 keV (by means of the Thomson stage) [3]. A polarimeter devoted to hard X-rays (*i.e.* above 20 keV) would be the natural complement to SXRP and would give invaluable information on the processes and emission mechanisms of X-ray sources.

Various physical processes which operate in cosmic sources can give rise to a significant degree of linear polarization in hard X-rays. Particularly interesting are the cyclotron lines from galactic sources, which are expected [4] to be linearly polarized up to almost 100%. More generally, in every astrophysical scenario in which hard X-rays are produced and/or transferred in a highly asymmetric geometry and/or in the presence of intense magnetic field, a certain degree of polarization is expected, due to radiative transfer processes or the emission mechanisms themselves (*e.g.* [1, 5]).

Many classes of hard X-ray sources are potentially emitters of linearly polarized radiation. In sect. 3 we will discuss the astrophysical capabilities of the fiber polarimeter, using, as an example, the "standard" case of the Crab Nebula.

2. – The Compton scattering polarimeter

The Compton scattering is sensitive to the linear polarization of the incident photon. In fact, the scattered photon is preferentially emitted in the direction perpendicular to the plane defined by the momentum vector and the electric vector of the impinging photon. This effect is described by the well-known Klein-Nishina formula [6]:

$$\mathrm{d}\sigma = \frac{1}{2} r_0^2 \left(\frac{E}{E_0} \right)^2 \left[\frac{E}{E_0} + \frac{E_0}{E} - 2 \sin^2 \theta \cos^2 \varphi \right] \mathrm{d}\Omega \,, \tag{1}$$

where E and E_0 are the energy of the scattered and incident photons, respectively, r_0 is the classic electron radius, θ is the scattering angle and the azimuthal angle φ is that between the electric vector of the incident photon and the scattering plane. As can be easily seen from the formula, a Compton polarimeter is most efficient as the scattering angle θ approaches $\pi/2$.

The basic Compton polarimeter design consists of an analyser and a detector which is rotated around the pointing axis. The number of the detected counts is modulated in the azimuthal plane as $N(\phi) = a_0 + a_1 \cos^2(\phi + \phi_0)$. For a 100% linearly polarized photon beam the counts vary from $N_{\mathrm{max}} (= a_0 + a_1)$ to $N_{\mathrm{min}} (= a_0)$. The sensitivity of the instrument to linearly polarized radiation is then characterized in terms of the *modulation factor* $\mu = (N_{\mathrm{max}} - N_{\mathrm{min}})/(N_{\mathrm{max}} + N_{\mathrm{min}})$.

For a given source of flux S, the sensitivity of the polarimeter, in a given energy band, depends on the instrumental parameters such as the background counting rate B, area A and efficiency ε. In particular, the *Minimum Detectable Polarization* from a certain source, observed for a time T [7]

$$\mathrm{MDP}\,(99\%) = \frac{4.29}{\varepsilon \mu S} \sqrt{\frac{\varepsilon S + B}{AT}} \tag{2}$$

fixes the statistical limit, at the 99% confidence level, to the polarimetric sensitivity of the instrument.

3. – The fiber polarimeter design and simulated performances

A Compton polarimeter for the hard-X-ray band (nominally 20–200 keV) typically uses an active scatterer together with a detector with high stopping power. Following this general scheme, the fiber polarimeter is composed by a bench of low-Z, fiber-shaped scintillators, surrounded by a wall of high-atomic-number fibers. Each of the low-Z fibers (*i.e.* plastic scintillator) has a hexagonal, $\sim 3.4\ \mathrm{mm}^2$ cross-section and a symmetry axis parallel to the pointing direction. On the other hand, the high-Z fibers (*i.e.* caesium iodide) have half-hexagonal cross-section in order to exactly surround the plastic fibers and give rise to a global hexagonal polarimeter geometry, with $1.66\ \mathrm{cm}^2$ area. The fiber height (the same for the two kind of fibers) derives from a compromise between the optimization of efficiency and modulation factor, and the minimization of background. It can be shown that this value should range between 5 and 10 cm. In the following examples we use 5 cm fibers.

This polarimeter operates searching for coincidences between a plastic and a CsI fiber. Such an event can be interpreted as determined by a photon Compton scattered from the low-Z fiber and detected by the high-Z one. In principle the roles of scatterer and absorber could be reversed, but the absorption probability is dominant over the scattering one in CsI up to 250–300 keV. The first ionization event, in plastic, is expected to have an energy of the order of $E_0/m_e c^2$ (for a scattering angle close to $\pi/2$). It allows to reconstruct the direction of the scattered photon when the coincidence with the more energetic event in CsI is detected. Such a direction is taken to be the one of the line connecting the centers of the two involved fibers.

The reconstruction of the linear polarization of the impinging photon beam can be carried out by building up a phase histogram of the recorded directions of the source photons. From the amplitude and phase of the resulting histogram we can determine the polarization degree and angle of the source. The reconstruction of the energy of the original photon is possible with the uncertainty of the energy deposition occurred in the first ionization (*i.e.* in plastic). This is because the photoelectric absorption in CsI occurs when the photon has lost an energy of the order of $E_0/m_e c^2$, that at the lower energies (where the cosmic sources have stronger fluxes) is of the order of 10% or less. A (modest) spectral capability is therefore expected.

In principle such a device can operate without rotating around the pointing axis, but in this way the deconvolution of data could be very cumbersome. This is because each pair of fibers represents an "elementary polarimeter" with its own phase, efficiency and modulation factor. The latter two are determined from the distance and the solid angle between the two fibers. The various directions would then be covered in the polarimeter with very different efficiencies. To overcome this problem a rotation of the entire polarimeter is strongly recommended, in order to have the same polarimetric efficiency to all the polarization directions.

The single polarimeter described so far has an effective area of only $1.66\ \mathrm{cm}^2$. Because of the inefficiency of hard X-ray concentrators at present time, such an effective area is unacceptably small for astrophysical purposes. A larger area, up to several thousands of square centimeters, can be obtained by a repeated structure of single polarimeters. The light signal coming from fibers in the same position in different polarimeters can be fed into the same photomultiplier and electronic processing chain, in order to minimize the complexity of the read-out electronics.

The "cross-talk" noise (*i.e.* represented by the pairs composed of one event in one single polarimeter and the other in an adjacent polarimeter) can be reduced by inserting a high-Z and dense thin shield around each single polarimeter. The

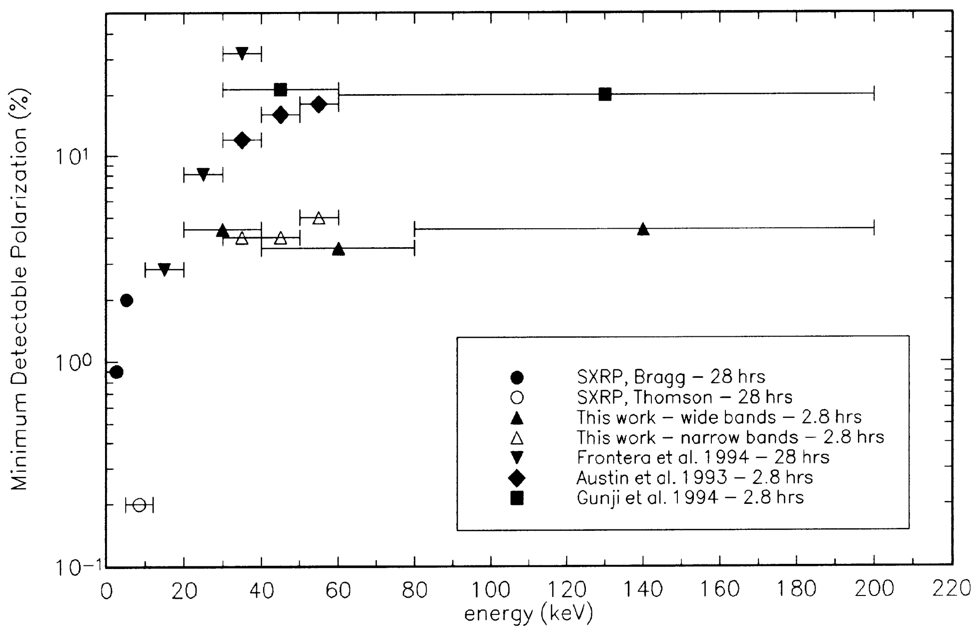

Fig. 1. – Simulated performances of the fiber polarimeter in terms of Minimum Detectable Polarization (at 99% confidence level) for the Crab Nebula, compared with other polarimetric experiments, in various energy bands. For two satellite experiments (SXRP and Frontera *et al.*) an observing time of 28 hours has been taken into account.

environmental noise (*i.e.* pairs due to background events) and the instrumental noise (*i.e.* pairs composed by a background event and a dark current event) can be easily minimized by performing very fast coincidences between the plastic and the CsI fibers. To this aim, the use of other high-Z scintillator than CsI, whose decay constant is around 1 μs, is recommended. One possible choice could be the YAP [8].

The performances of the fiber polarimeter have been widely studied by means of Monte Carlo simulations, for various configurations, materials and energies. The results are shown in [9] and [10].

We now compare the astrophysical performances of our polarimeter with other X-ray polarimeters, currently under development. In fig. 1 we present the polarimetric sensitivity of the fiber polarimeter for the Crab Nebula, in three narrow energy bands between 30 and 60 keV, and in three wider energy bands over the 20–200 keV range, for a 2.8 hours observing time. Here we assume a signal-to-noise ratio of 1, in a balloon-borne experiment of 1000 cm^2 effective area.

In the figure the sensitivities of SXRP are reported as a reference, although the operative energy band does not overlap the fiber polarimeter one. Note that the SXRP sensitivities, as well as those of the Bragg concentrators of [11], are obtained considering a satellite observing time of 28 hours. On the other hand, in the sensitivity calculations of the fiber polarimeter, as well as of the Compton polarimeter of [12] and of the hard X-ray imager of [13] 2.8 hours observing time has been used.

It should be noted that the fiber polarimeter attains sensitivities comparable to those of SXRP, but at higher energies (where the source is much weaker) and in one tenth of the SXRP observing time.

4. – Final remarks

We have presented the design and some simulated astrophysical performances of a hard-X-ray Compton polarimeter using fiber-shaped scintillators.

Many technical details have to be defined and studied in order to maximize the instrumental performances. Special attention and care has to be devoted to the optical coupling of the fibers to the read-out system. In this respect, it could be probably more efficient to employ fiber-shaped scintillators (with a proper reflecting coverage) rather than scintillating fibers, whose light capture coefficient is usually of the order of 5%. Another goal is the background minimization, which is based on the capability of performing very fast coincidences (on tenths of nanoseconds time scales), besides the use of the classical background reduction techniques.

By using conservative values for instrumental parameters, such as the optical coupling efficiency, the read-out capability and the background counting rate, the astrophysical performances of this instrument turn out to be at the highest levels in the hard X-ray polarimetry instrumentation scenario.

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