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Techniques and detectors for polarimetry in X-ray astronomy

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Abstract

Polarimeters flown so far were based on the *Thomson* scattering and *Bragg* diffraction with intrinsically limited sensitivity. In the present paper, we review the experiments based on those techniques and discuss possible optimization and implementation for X-ray astronomy.

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1. The role of polarimetry in X-ray astronomy

Soon after the start, in 1962, of X-ray Astronomy, polarimetry was widely acknowledged as a powerful tool to investigate the physics of X-ray sources.

Polarimeters on-board of rockets and satellite were launched a few years after, providing the only positive result of the polarization of the Crab Nebula which stated that synchrotron emission extends up to X-rays.

1.1. The physics

According to a vast theoretical literature most of X-ray sources should show an important degree of polarization deriving from the emission process itself: cyclotron, synchrotron, non-thermal Bremsstrahlung [1–3].

But also from the radiation transfer, when geometrical asymmetry in the scatterer (accretion disks) selects the scattering angles to the observer [3,4]. Birefringence effects due to magnetic fields of the order of 10^{13} gauss in a pulsar [6,7], up to 10^{15} gauss in a magnetar can polarize the thermal radiation.

1.2. Galactic X-ray sources

X-ray pulsators are binary systems, with an ordinary star accreting matter onto the poles of a highly magnetized neutron star. Both the emission and the transfer probabilities strongly depend on the polarization. Especially near to the cyclotron resonance frequency, high polarization is expected, with an angle swinging around the rotation axis and giving a direct vision of the geometry of the

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system [5]. In Low Mass X-ray Binaries time resolved polarimetry of Quasi-Periodic Oscillations, will disentangle the direct emission of the star from that scattered by disk [8]. In isolated neutron stars (radio-pulsars, Soft Gamma-Ray Repeaters) a phase resolved polarimetry should show the spatial structure of the magnetic field, through birefringence effects [9].

1.3. Extragalactic sources

In the inner regions of an AGN the radiation can be polarized by inverse *Compton* scattering on high-energy electrons of the disk [10,4]. The polarization plane, bent by General Relativity effects, will rotate continuously with energy, being the signature of the presence of a black-hole [11,12]. Photoionization in bright sources extends the scattering to low energies [13]. Blazar polarimetry will probe geometry and energy distributions within the jet [14]. Non-thermal component (and, possibly, lines by resonant scattering [15] in clusters) and Gamma-Ray Burst Afterglows should be polarized as well.

2. The statistics of X-ray polarimetry

A polarimeter deals with counting rate statistics. The goodness of a practical implementation depends mainly on the modulation factor μ, which represents the response of a polarimeter to a 100% polarized source as the normalized half-counting rate difference.

It spans from 0 (insensitive) to 1 (maximum sensitivity).

The degree of polarization P is a positive-definite quantity, with a non-Gaussian statistics. For a source counting rate S, background rate B and modulation factor μ is possible to define the sensitivity at 99% confidence level as the Minimum Detectable Polarization (MDP):

$$\mathrm{MDP} = \frac{4.29}{\mu S}\sqrt{\frac{S+B}{T}}. \quad (1)$$

By Fourier series expansion of the modulation curve, the polarization information is contained in the second-order coefficient (a_2) normalized to the zero-order (a_0). The polarization of the source is derived from

$$P = \frac{a_2}{a_0}\frac{S+B}{\mu S}. \quad (2)$$

3. Classical techniques: Bragg diffraction and Thomson scattering

3.1. Bragg diffraction and flown polarimeters

A polarimeter based on *Bragg* diffraction [16] at 45° incidence angle, reflects only the X-ray polarized perpendicular to the plane of incidence and, therefore, is a *dispersive* technique (Fig. 1). A rotating crystal produces a reflected beam modulated by the polarization at twice the angular velocity with μ very close to 1. The bandwidth and thence the counting rate from a source with a continuum spectrum, is maximized by using mosaic graphite crystals made by small crystal domains slightly misaligned (spread of 0.8°). Graphite has a very large experimental integrated reflectivity (larger than 10^{-3} rad) compared with other crystals. The pyrolytic graphite has at 45° a first-order reflection of 2.62 keV. Polarimeters based on *Bragg* diffraction flown on-board rockets [17,18] with large effective area of $4 \times 287\,\mathrm{cm}^2$ and on-board of satellite as in OSO-8 (see Fig. 2), (with effective area of $2 \times 140\,\mathrm{cm}^2$) [19,21] and Ariel-5 ($234\,\mathrm{cm}^2$) [20]. *Bragg* crystal polarimeters are built by gluing small mosaic crystals on sectors of parabolic surface, therefore increasing the collecting/detector area (28 for OSO-8). The bandwidth (0.4 keV at the first-order for OSO-8), made possible the only positive detection to-date of X-ray polarization from a celestial source [17,21,22] (Fig. 2) and many upper limits [23]. Flat crystals in Ariel-5 provided only large upper-limits on the brightest X-ray sources [20].

3.2. Thomson scattering and flown polarimeters

The azimuth distribution of the scattered photons brings memory of the polarization angle of the incident beam. At 90° in the Thomson regime the dependence is reduced to $\cos^2\varphi$ and the

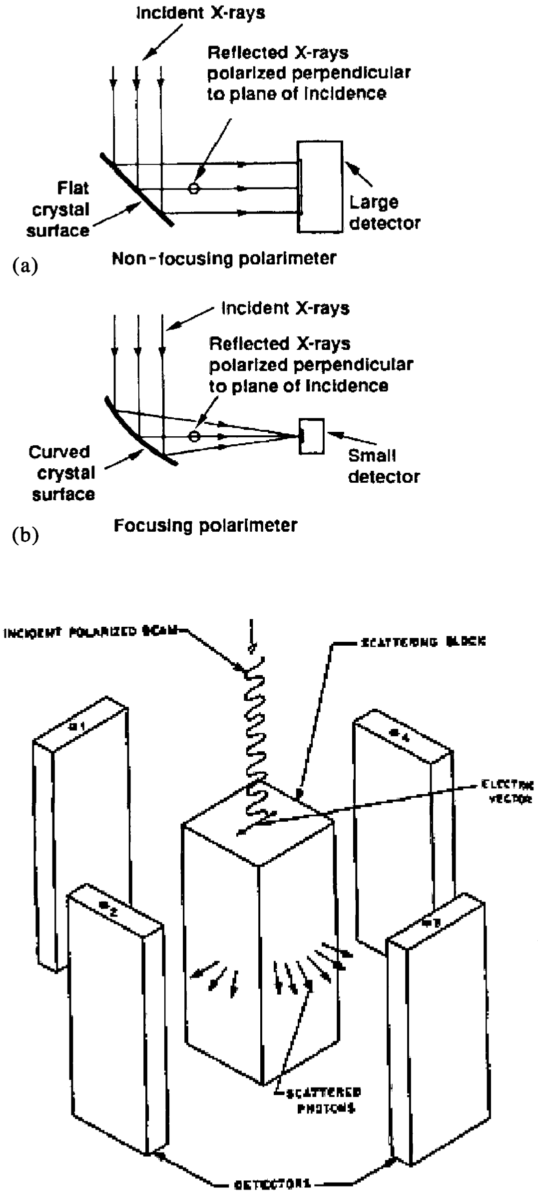

Fig. 1. Concept of *Bragg* crystal dispersive polarimeter (top) and *Thomson* scattering non-dispersive polarimeter (bottom).

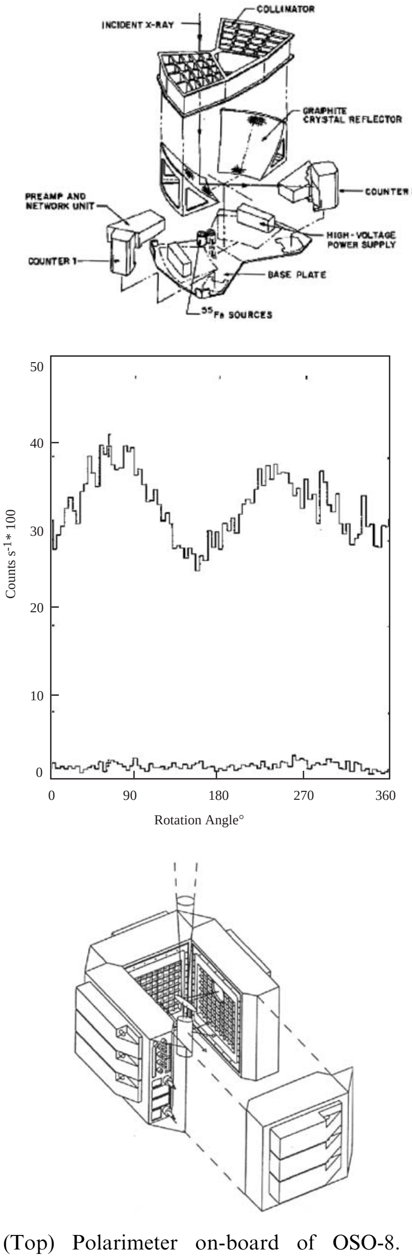

Fig. 2. (Top) Polarimeter on-board of OSO-8. (Middle) Modulation curve from the Crab Nebula [22]. (Bottom) The focal plane of SXRP [30] with detectors and analyzers.

polarimeter is ideal. Practical implementations accept larger angles at the expense of the modulation factor (Fig. 1) *Thomson* scattering competes at low energy with photoelectric absorption, requiring the use of lithium (the lowest-Z, solid material at room temperature). It must be encapsulated with beryllium or plastics and 4-keV is a lower boundary for the energy. Multiple scattering and self-absorption limit the section. Many blocks of large surfaces are needed with poor collecting/

detector area. Experiments based on *Thomson* scattering were only performed on board-of rockets with meager results [24,25,17]. In those experiments a set (16 or 28) of lithium blocks ($5\,\text{cm} \times 5\,\text{cm} \times 12.7\,\text{cm}$) were encircled, each one, by 4 proportional counters with equivalent size.

4. SXRP: a focal plane polarimeter

The Stellar X-ray polarimeter (SXRP) [26,27] is built to perform polarimetry in the 2–15 keV band, at the focus (Fig. 2) of a telescope (effective area of $1670\,\text{cm}^2$ at 2 keV and $107\,\text{cm}^2$ at 15 keV), aboard the Russian space mission *Spectrum-X-Γ*. SXRP exploits, simultaneously, both *classical* techniques by means of a stacked configuration of a thin graphite mosaic crystal [28,29] and a lithium rod encapsulated in a beryllium can, encircled by four imaging multiwire proportional counters [30] with a beryllium window. The graphite crystal reflects X-rays on a secondary focus at 9 cm from the optical axis across a thin (50 μm) beryllium window on one of the four detectors. Higher energy X-rays are scattered by a 7 cm long 3 cm diameter lithium rod placed under the crystal and are collected by the four imaging detectors. The whole instrument rotates at 0.5 rpm around the telescope axis. The expected sensitivity of SXRP will be one order of magnitude larger than those of OSO-8. For source strength larger than $6 \times 10^{-10}\,\text{erg}\,\text{cm}^{-2}\,\text{s}^{-1}$, the *Thomson* stage is more sensitive than the *Bragg* stage due to its larger effective area. At smaller fluxes the *Bragg* stage is more sensitive because it takes advantage of the imaging capability. For 10^5 s integration time, the MDP (as in Eq. (1)), is 0.35% for a source as strong as the Crab, while the access to extragalactic sources would still be limited only to the very brightest ones.

An additional problem, for SXRP as for any polarimeter, is the requirement on calibration of the response to both polarized and unpolarized source. Any deviations from cylindrical symmetry, material inhomogenities, or pointing misalignments would be a source of serious systematic errors, potentially higher than the signal itself [31–33]. Additional spurious effects may derive from solar X-rays scattered from the Earth atmosphere, anisotropy of particle background, shape of the telescope Point Spread Function, variation of roundness and off-axis distortions. Rotation and calibration of the response to unpolarized radiation at level of 1% percent is demanded. Being collimated fluorescent sources too weak, X-ray tubes should be unpolarized better that 1%, which is difficult to achieve and to check. The response to a converging beam from a telescope can be measured in laboratory by the use of small converging beams produced by double *Bragg* crystals [34,35]. The calibration after integration with the telescope would require very large facilities. Results of independent measurement on the polarimeter and the optics and alignments, must be integrated in a detailed Monte Carlo simulation.

5. Instrument development and the future of X-ray polarimetry

Bragg crystal polarimeters of parabolic shape concentrate a large collecting area on small detectors and a complete revolution surface permits a simultaneous analysis of all the azimuth angles. Polarimeters based on stack of many crystals [5] would attenuate the bandwidth limitation. In the soft X-rays (0.25 keV) may pay a role a proposed polarimeter made by coating three sectors (1 m outer diameter) of a parabolic surface of revolution with a Ni/C multilayer with different spacing [36,37] for sensitivity at multiple energies.

For scattering polarimeters it is difficult to foresee a significant improvement with the conventional set-up. The use of liquid helium or solid hydrogen is quite unrealistic and LiH represents a minor improvement. A major limitation of the scattering polarimeters is the loss of any information on the interaction with the passive scatterer that spoils the statistical sensitivity and increases systematic effects. The background is high and the advantage of the use of an optics is lost. But, if the scatterer itself is a detector, the temporal coincidence will enormously reduce the background. If the detector is finely subdivided it provides the interaction point and give a real image in the focus of an optics. The signal competes with the background of a pixel only, enormously increasing the sensitivity. The modern detector technology can provide various solutions for finely subdivided detectors, such as bundles of scintillating fibers or multi-pixel solid state detectors. But fibers are based on C (effective at $>15\,\text{keV}$), or CsI (effective at $>200\,\text{keV}$) and the second on Si (effective $>25\,\text{keV}$) or CdTe (effective $>400\,\text{keV}$). The classical X-ray band (2–10 keV) is forbidden but plastic fibers or Si detectors could operate in the focus of future high-energy optics.

Large arrays, finely subdivided, have been anyway proposed to increase sensitivity without unsustainable systematic effects. A *Compton* polarimeter based on Germanium microstrip detectors with bi-dimensional read-out has been tested [38]: it is effective for very hard X-ray. The array of CsI and CdTe detectors of the IBIS imager onboard INTEGRAL has some polarimetric sensitivity but only above 250 keV and only for the brightest sources [39]. Actually in the X-ray range the energy lost in the scattering is a small fraction of the total: therefore a good detector for the scatterer is not good for the total absorption. A possible solution is to use a low Z detector as scatterer and a high Z detector as total absorber as implemented, e.g. by Sakurai [40] and as proposed by Costa et al. [41] for a finely subdivided design (Fig. 3).

The new frontier in this field is the Photoemission. The photoelectrons are emitted with a $\cos^2$ distribution around the electric vector plane. For 20 years astrophysicists have tried to use this effect as an analyzer of polarization by detecting the extension of the photoelectron track. Nowadays such devices are available. The most evolved is the micropattern gas chamber capable to resolve the track in several pixels [42]. The interaction point can be reconstructed and positioned with precision of the order of $100\,\mu\text{m}$, the modulation factor is high (even $>50\%$) and no rotation is needed. The properties of this device, far better than the conventional devices, are the subject of another paper in this same volume [43]. A micropattern polarimeter in the focus of a large optics (of the class of XMM-Newton or, much better, in the XEUS telescope, under study by ESA) could attack most of the problems discussed by theoretical analysis on a very extended sample of sources of all the classes of interest.

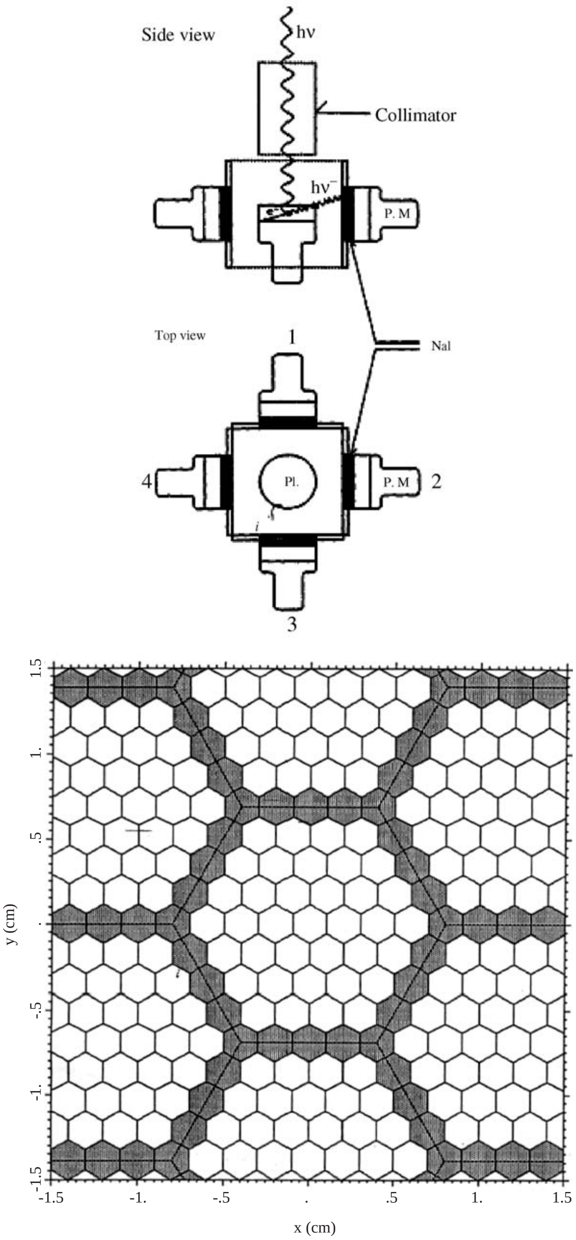

Fig. 3. Compton scattering active polarimeters. Basic design (Top) [40]. A finely subdivided design (Bottom) [41].

No polarimeter is presently foreseen aboard any future mission. This is partially due to the moderate appeal of the conventional technique and to the expectations invested on SXRP, whose future is now very dubitable. With the photoelectric polarimetry a new big telescope totally or partially devoted to this subtopic can be proposed. Also a small mission seriously attacking most of the galactic targets and touching the extragalactic domain could be meaningful.

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