PROCEEDINGS OF SCIENCE

X-ray Polarimetry

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Since the birth of X-ray astronomy, spectral, spatial and timing observations improved dramatically, procuring a wealth of information on the majority of the classes of the celestial sources. X-ray polarimetry, instead, remained basically un-probed. Still it promises to provide additional information procuring two new observable quantities, the degree and the angle of polarization. X-ray polarimetry will be performed in the near future by GEMS (Gravity and Extreme Magnetism SMEX) scheduled for a launch in 2014. The techniques to measure X-ray polarization are presented together with the main scientific objectives.

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1. The role of X-ray Polarimetry.

Soon after the beginning, 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 satellites were launched a few years later, providing, as the only positive result, the measurement of the polarization of the Crab Nebula, which meant that synchrotron emission extends up to X-rays. According to an extensive theoretical literature most X-ray sources should show an important degree of polarization deriving from the emission process itself: cyclotron, synchrotron, non-thermal Bremsstrahlung [1],[2],[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 pulsars [5] and up to 10^{15} gauss in magnetars can polarize the thermal radiation.

2. Statistics of X-ray polarization.

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 one can define the sensitivity at the 99% confidence level as the Minimum Detectable Polarization (MDP):

$$MDP = \frac{4.29}{\mu \times S} \times \sqrt{\frac{S+B}{T}} \tag{2.1}$$

It is clear from the above equation that the number of counts required to arrive at an MDP of 1% with an average modulation factor of 50%, and negligible background, is far larger ($\sim 7\ 10^5$ counts) than the number of counts that are necessary for the measurement of a spectral slope ($\sim$ 100) or for the detection of an X-ray celestial source ($\sim$ 10).

3. The classical techniques: Bragg diffraction and Thomson scattering.

A polarimeter based on Bragg diffraction at 45° incidence angle, reflects only X-rays polarized perpendicular to the plane of incidence and, it is, therefore, a dispersive technique. Mosaic graphite crystals, working at 2.61 keV and at higher orders, have a very large experimental integrated reflectivity (greater than 10^{-3} rad) when compared with other crystals. Polarimeters based on Bragg diffraction were flown on-board rockets [6] and on-board of satellites. The polarimeter on OSO-8 made possible the only positive detection to-date of X-ray polarization from a celestial source [7].

The azimuthal distribution of the scattered photons, also, reflects the polarization angle of the incident beam. Thomson scattering competes at low energy with photoelectric absorption, requiring the use of lithium. Multiple scattering and self-absorption limit the sensitivity. Experiments based on Thomson scattering were only performed on board-of rockets with meager results.

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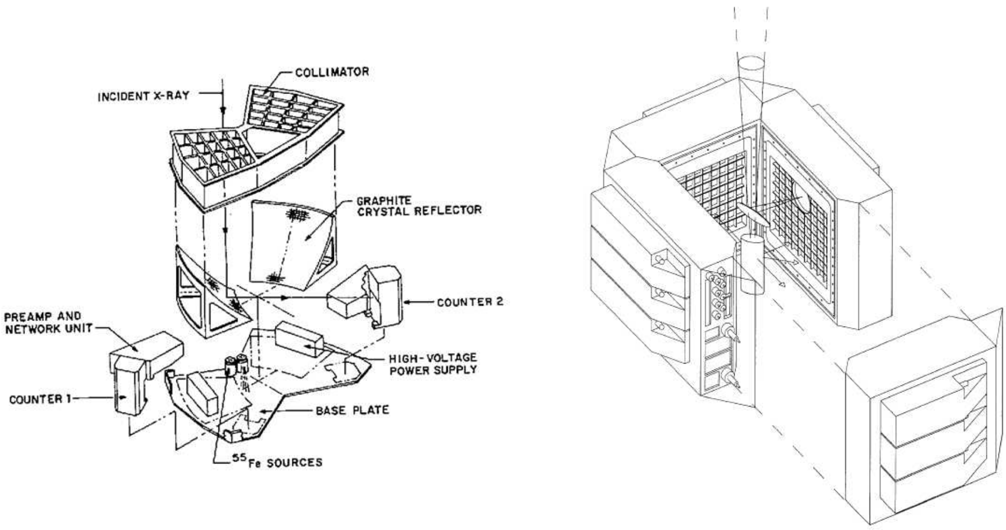
4. The stellar X-ray Polarimeter (SXRP).

The Stellar X-ray polarimeter (SXRP) [8] was designed and built to perform polarimetry in the 2-15 keV band, at the focus of a large telescope (SODART) aboard the former Russian space mission Spectrum-X-Gamma. SXRP uses a stack configuration of a thin graphite mosaic crystal and a lithium rod encapsulated in a beryllium can, encircled by four imaging multi-wire proportional counters (see fig.1(b)). SXRP was aimed at studying galactic sources while the access to extragalactic sources would still be limited to only the very brightest ones. An additional problem, for SXRP, is that any deviations from cylindrical symmetry, material inhomogeneities, or pointing misalignments would be a source of serious systematic errors, potentially higher than the signal itself. Additional spurious effects may result from the shape of the telescope Point Spread Function, variation of roundness and off-axis distortions. Unfortunately the Spectrum X-Gamma satellite with SODART telescopes was never realized although most of scientific instruments and the telescopes were completed.



(a) (b)

Figure 1: (**a**). The Bragg diffraction polarimeter on-board OSO-8. (**b**) The Stellar X-ray Polarimeter at the focus of a SODART telescope (Bragg diffraction and Thomson scattering). The SXRP flight model was fully tested and calibrated.

5. Modern polarimetry: the photoelectric effect.

Modern polarimeters dedicated to X-ray astronomy exploit the photoelectric effect resolving most of the problems connected with Thomson/Bragg polarimeters. The exploitation of the photoelectric effect was tried very long ago, but only since five-ten years was it possible to devise photoelectric polarimeters that are mature for a space mission. The photoelectric effect is sensitive to polarization, the polarization vector and direction of emission of the photoelectron being related by a cos^2 dependance. It has been efficiently exploited by first developing [9] [10] [11] a device capable to collect and image the charge produced by the track, measuring the photon interaction point and the photoelectron emission direction (the Gas Pixel Detector, GPD). Another approach [17] images the track with a Time Projection Chamber device (TPC) by using simultaneously the information on time and space. The TPC cannot detect the instant of the photon conversion, therefore the image is lost, but it decouples the drift length from the absorption depth.

5.1 The Gas Pixel Detector.

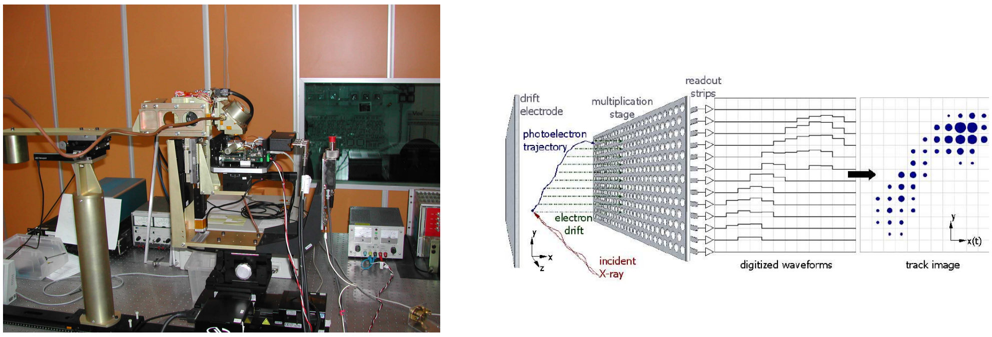
The Gas Pixel Detector aims to preserve as much as possible the azimuthal symmetry in the response allowing for a non-rotating device and it is the result of a collaboration between INFN-Pisa and IASF-Rome/INAF. A photon crosses a beryllium window and it is absorbed in the gas gap, the photoelectron produces a track. The track drifts toward the multiplication stage that is the GEM (Gas Electron Multiplier) which is a dielectric foil metallized on both side and perforated by microscopic holes (30 μm diameter, 50 μm pitch) and it is then collected by the pixellated anode plane that is the upper layer of an ASIC chip (15 $\times$ 15 mm^2, 105600 hexagonal pixels with a 50 μm pitch). Each pixel is directly connected to an underlying full electronics chain including a signal pre-processing function for the automatic localization of the event coordinates. The polarization information is derived directly by the angular distribution of the emission direction of the tracks produced by the photoelectrons. The incoming direction of the photons is parallel to the drift direction and the impact point is derived with high precision: the device has very good imaging capability limited only by the Point Spread Function of the optics. The GPD with different filling mixtures has been fully tested and calibrated (see fig.2(a)) [15] and it has been proposed in different X-ray astronomy missions such as POLARIX [12], NHXM [14] and IXO [13].

5.2 The Time Projection Chamber polarimeter.

The Time Projection Chamber (TPC) polarimeter forms two-dimensional images turning a 1-D device in a 2-D device by using timing information. It uses a micro-pattern proportional counter. The photons arrive parallel to the strip direction. The ionization electrons drift with a constant velocity to the cathode where they are multiplied by a GEM. The charge is then collected on the strips. A track image projected on the plane normal to the X-ray incidence is formed binning the data into pixels with coordinates defined by strip location in one dimension and arrival time, derived by means of a waveforms digitizer, multiplied by the drift velocity in the orthogonal dimension. In this geometry the quantum efficiency increases with the absorption depth of the detector and it is independent of the average electron drift distance. The modulation can still be high simultaneously to the quantum efficiency. However the image is lost because it is not possible to derive the impact point. Also the azimuthal symmetry is lost and rotation becomes therefore necessary.

6. Gravity and Extreme Magnetism Explorer SMEX (GEMS).

The GEMS mission [18] will be the first mission dedicated to the measurement of the X-ray polarization after OSO-8. It will be launched in 2014. GEMS hosts two TPC polarimeters, sensitive between 2 and 10 keV, at the focus of two Suzaku-like mirrors without the outer shells. The satellite will be in a Low Earth Orbit and it will rotate at a 0.1 RPM. On board there is also



(a) (b)

Figure 2: (**a**). The GPD installed at the calibration facility [16] that produces monochromatic and polarized beams between 1.6 keV and 17.4 keV. (**b**) The TPC approach to measure X-ray polarization.

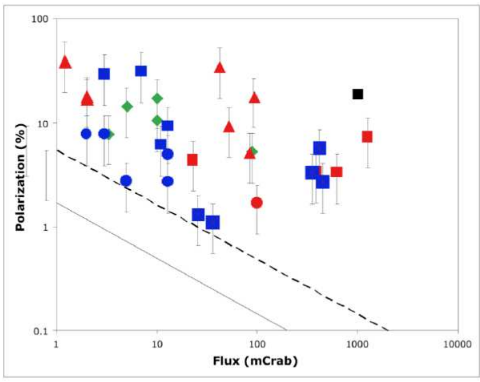


Figure 3: Minimum Detectable Polarization (10^5 s, dashed, and 10^6 s, gray) for GEMS compared with theoretical expectations. Square is the Crab Nebula. Are shown, also, black holes (blue), neutron stars (red), and Supernova Remnants (green).

a multi-layer Bragg diffraction polarimeter sensitive at 0.5 keV. The sensitivity will be 1% for a 10 mCrab source with an observation of 3.3×10^5 seconds. The mission will last for 9 months following an in-orbit checkout of the spacecraft and instrument, lasting one month. There is a possibility of an extension, the Science Enhancement Option, which would last an additional 15 months, with observations competitively selected in a peer-reviewed process. Baseline targets are (see fig. 3) : (1) Stellar Black Holes, (2) Seyferts & Quasars, (3) Blazars, (4) Rotation-powered Pulsars, (5) Accretion-powered Pulsars, (6) Supernova Remnants

7. Conclusion.

X-ray polarimetry is a valuable tool for modelling almost any kind of celestial sources. Next years are very promising with GEMS and hard-X ray polarimeters [19] not discussed here.

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