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Polarimetry: a (new?) tool for X-ray astronomy

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Abstract. Polarimetry is today the last unexplored probe in X-ray astronomy. Despite the first attempts to measure polarization from celestial sources were performed in the seventies, namely at the very beginning of high energy astrophysics, only a successful detection has been reported in the case of the Crab Nebula. Today, however, photoelectric devices promise to achieve a much larger sensitivity than the instruments built so far. The Gas Pixel Detector, in particular, is a completely Italian project which has reached an outstanding readiness level. Currently it is included in many proposals of missions which have passed a certain degree of selection by national and international space agencies and could be launched in a few years. We review the status of the project and discuss the perspectives of measurement on board next satellite missions.

Key words. X-ray astronomy - Polarimetry - Future missions

1. Introduction

Polarimetry adds two more observables, the degree and the angle of polarization, to informations acquired by spectroscopy, timing and imaging. They are extensively exploited in astronomy to pinpoint non-thermal emission processes or to constrain the geometry of the sources. Unfortunately polarimetry is not available at energies above optical/UV wavelengths. This is particularly painful because the high energy sky is dominated by objects which emit predominantly non-thermal radiation and where the geometry of system has often a central role. Some examples are AGNs, the beamed emission from pulsars or the accretion from a disk on compact objects such as neutron stars, black holes or white dwarfs.

The importance of polarimetry has been stressed from many authors since the very beginning of X-ray astronomy (Novick 1975; Rees 1975). On the basis of these pioneering works and more recent results, we expect that almost all the sources in the X-ray sky should emit partially polarized radiation at least at the level of a few percent. Positive detections could discriminate among different models which are otherwise equivalent on the basis of current spectral or timing mea-

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surements, such as the emission geometry in pulsars (Dyks et al. 2004) or pulsars in binaries (Meszaros et al. 1988). Peculiar signatures in the polarization behavior should emerge in the presence of strong magnetic and gravitational fields. The different opacities in plasma for polarization modes perpendicular or parallel to the magnetic field (Canuto et al. 1971; Meszaros 1992) almost completely polarize the emission from the surface of neutron stars. As the radiation emerges, it is affected by gravitational bending (Pavlov & Zavlin 2000) and vacuum birefringence (Heyl et al. 2003) but the polarization retains a significant memory of the ratio between the mass and the radius of the neutron star. This would allow to constrain the equation of state of matter at superdense densities. Moreover the dependency with energy should be different in the case of pulsars and magnetars, providing an independent probe to test the strong magnetic field paradigm of the latter objects (Lai & Ho 2002). Other topics of fundamental physics could be also investigated. The expected rotation of the plane of polarization with energy for stellar-mass blackholes (Stark & Connors 1977; Connors et al. 1980) allows both to test the General Relativity in the strong field regime and measure the spin of the central black hole. The detection of a rotation of the polarization angle for distant sources could be the signature of vacuum birefringence expected in some theories of Quantum Gravity (Gambini & Pullin 1999; Mitrofanov 2003; Kaaret 2004).

Despite the paramount scientific importance of the X-ray polarization measurements, still today we register only the positive detection in the case of Crab Nebula. This was performed in soft X-rays in the seventies by the polarimeter on-board OSO-8 (Weisskopf et al. 1978), while a very high degree of polarization in soft gamma-rays was reported by INTEGRAL very recently (Dean et al. 2008; Forot et al. 2008).

The lack of experimental feedback to scientific expectations derives basically from the intrinsic difficulties to measure the polarization. Even with a perfect instrument which completely responds to polarization, several tens of thousands of photons are required to achieve a sensitivity of the order of 1%, namely the level expected for many astrophysical sources. Moreover the measurement of polarization is definite positive and then a spurious modulation is always measured. The instruments built so far, based on Bragg diffraction at 45° or Thomson/Compton scattering at 90°, have failed to achieve a sufficient trade-off between efficiency and good polarimetric response and/or control the systematics. Hence the polarimeters based on these classical techniques had been systematically descoped from large observatories, which were the only opportunities to collect a sufficient statistic thanks to large area telescopes.

Today the photoelectric devices are an effective alternative to classical techniques. They promise to fill the gap between polarimetry and the expectations which have emerged since the beginning of X-ray astronomy. In the following we describe one of the most advanced instrument at the moment, the Gas Pixel Detector, and outline the space missions proposed to exploit its large sensitivity.

2. The Gas Pixel Detector

The Gas Pixel Detector has been developed in Italy by INFN of Pisa and IASF/INAF of Rome (Costa et al. 2001; Bellazzini et al. 2006, 2007) and is based on absorption of X-ray photons in a gas cell. The photoelectric effect is a perfect analyzer for polarization. In the case of K-shell, which is the most involved in X-rays absorption, the photoelectric differential cross section is (Heitler 1954):

$$\frac{d\sigma_{ph}^{K}}{d\Omega} \sim \frac{\sin^2\theta\cos^2\phi}{(1+\beta\cos\theta)^4}, \tag{1}$$

where β is the photoelectron velocity in units of c and θ and ϕ are the latitudinal and the azimuthal emission angles respectively. The former is measured with respect to the incident direction and then the emission is more probable in the plane orthogonal, at least for soft X-rays. Instead ϕ is the angle that the direction of emission makes with the absorbed photon electric field. Hence the probability of emission in a certain direction is modulated as a

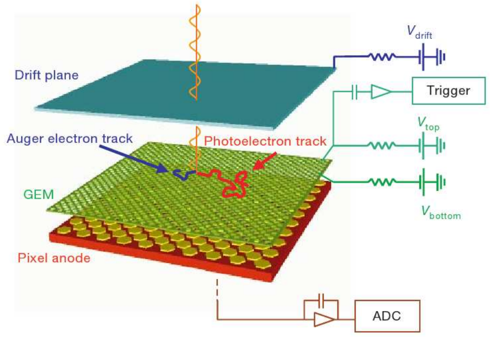

Fig. 1. Principle of operation of the Gas Pixel Detector (Costa et al. 2001).

$\cos^2$ function for polarized photons. The polarimeters based on the photoelectric effect basically exploit the azimuthal asymmetry in the photoelectrons emission to derive the polarization. In particular, gas detectors are able to reconstruct the initial direction of emission by imaging the path of photoelectrons.

The operation of the Gas Pixel Detector is sketched in Fig. 1. The X-ray photon is absorbed in a gas cell. As the electron propagates in the gas, it loses energy by ionization and produces electron-ion pairs (primary pairs) which drift and are amplified in an electric field generated by a Gas Electron Multiplier (GEM). The secondary pairs produced are eventually collected by a fine sub-divided pixel detector. Low-Z mixtures are typically employed in the gas cell to limit the scattering of photoelectrons.

Basically the GPD is a modern proportional counter, with the breakthrough capability to resolve the tracks thanks to the small pixel size of the read-out chip. The current detector (Bellazzini et al. 2006) is based on the third generation of an Application Specific Integrated Circuit (ASIC) chip. The active area is 15×15 mm^2 and is composed of 105600 pixels organized in a hexagonal pattern. The accurate sampling of the track of photoelectrons, even at low energy, is possible thanks to the small size of the pixels (50 μm).

A key characteristic of the GPD is that it has also imaging, spectral and timing capabilities. The first derives from the possibility to reconstruct the absorption point of the photons in the gas cell together with the initial direction of photoelectron emission. The spatial resolution is of the order of 150 μm. The timing and spectral informations are currently obtained by the trigger of the acquisition and the total charge collected by the pixels, but the goal is to get them from the signal of the GEM. This should assure a good timing ($\sim$10 μs) and spectral resolution (20% at 6 keV, against $\lesssim$30% of the current prototype).

The cell containing the mixture is sealed but it can be refilled to test different mixtures. Typically they are composed of helium and dimethyl ether to obtain the best performaces in the energy range ∼2-10 keV. No degradation of the performances has been measured during a period > 1 year of continuous operation (Bellazzini et al. 2007). The lack of any refilling system is obviously a great advantage for space use: the whole prototype used in the laboratory weights only 1.6 kg and it is contained in a box 140×190×70 mm^3 which includes the detector and the read-out electronic.

The Gas Pixel Detector is essentially ready for the use on-board next space-borne missions. The performances have achieved the results expected on the basis of a Monte Carlo simulations (Muleri et al. 2008), which promise a breakthrough increase of sensitivity with respect to previous instruments. Moreover no major issues are expected in the use of the instrument in orbit. The possibility of destructive discharges is reduced by the very low electron amplification required in the gas cell. The GPD has survived without any degradation after to the irradiation of iron ions corresponding to several years in orbit performed in the Heavy Ion Medical Accelerator in Chiba (HIMAC) and to vibrations and thermovacuum tests between -15 and 45°C.

3. Future missions

The GPD will be placed in orbit in the focus of a X-ray telescope to collect a sufficient number of photons to perform polarimetry at the level of 1% and below. Two different possibilities of missions have emerged in the last few years. The first is a small pathfinder satellite, eventually devoted to X-ray polarimetry, to be launched in a few years. This is a low-cost mission with a small X-ray optics designed to be versatile and address at best to many different scientific topics. A particularly interesting possibility is the use a small cluster of indentical telescopes. Indeed polarimetry is limited to relatively bright sources and the background is negligible in all practical situations. Then data from different instruments can be summed without a significant loss of sensitivity with respect to a single large optics. This is very important for small missions since a large collecting area can be reached with many identical units which have a much lower cost than a single optics of equivalent area.

The second possibility is the inclusion of the GPD in a large observatory, the *International X-ray Observatory* (IXO). The large optics (~2 m^2 at 2 keV) would allow to reduce of more than an order of magnitude the observation time. This would open the way to polarimetry of even faint extragalactic sources and more detailed studies on the most interesting sources singled out from the results of pathfinders.

3.1. Pathfinders

Two possibilities of small missions are currently under study. The first is a completely Italian mission, *PolariX*, proposed to the Italian space agency (ASI) and dedicated to X-ray polarimetry (Costa et al. 2006). PolariX was selected for a phase A study at the end of 2007 in competition with four other proposals: the study finished in December 2008 and currently PolariX is waiting for the downselection to two approved missions. If selected it will be launched in mid 2014.

The costs of the mission are kept low by using three telescopes already built for the Jet-X instrument, supposed to fly on-board *Spectrum X-ray Gamma* which however has never been launched. The spare unit is today working successfully in the *X-ray Telescope* instrument onboard the *Swift* satellite. A GPD, filled with a He-DME mixture sensitive in the 2-10 keV energy range, is in each focal plane together with a filter wheel to put in front of the detectors calibration sources, gray filters and diaphragms.

The second opportunity is to include two polarimeters, with a focal plane layout similar to PolariX (Soffitta et al. 2008), on-board the Chinese mission HXMT (*Hard X-ray Modulation Telescope*, Li 2007). This is devoted to study hard X-ray emission of astrophysical sources with three slat-collimated instruments. The main scientific objective of the mission is an all-sky survey, but pointed observations are foreseen to study X-ray binaries and Supernova remnants for about a half of observation time. Hard X-ray emission and polarimetry are often related since non thermal processes can emerge both with hard tails and polarized radiation. EXP^2 (*Efficient X-ray Photoelectric Polarimeter*) would allow to join the study of the polarization to that of hard X-rays performed with HXMT. It has been approved by ASI which is currently negotiating its inclusion on-board HXMT with the Chinese space agency.

There are important differences between PolariX and EXP^2. The first is a mission dedicated to X-ray polarimetry, with a good angular resolution (~24 arcsec) achieved thanks to the long focal length (3.5 m). Instead the focal length of EXP^2 is limited by the volume available but the optics can exploit the modern technology and actually reaches a larger area at low energy, where there is the peak sensitivity. However this class of missions is characterized by similar polarimetric performances and then in the following we assume PolariX as a benchmark. Since the profile is that of a small mission, long pointed observations (up to ~10 days) can be dedicated to single targets which are particularly interesting.

The observation time required to achieve a certain level of Minimum Detectable Polarization at a statistical confidence of 99% (MDP) as a function of the flux is reported in Fig. 2 for PolariX. We expect to detect a polarization higher than 1% with an observation of one day (~100 ks) for 100 mCrab source (corresponding to 2.3 10^{-9} erg/cm^2/s between 2 and 10 keV).

PolariX will be able to measure the spin of galactic black holes by means of the rota-

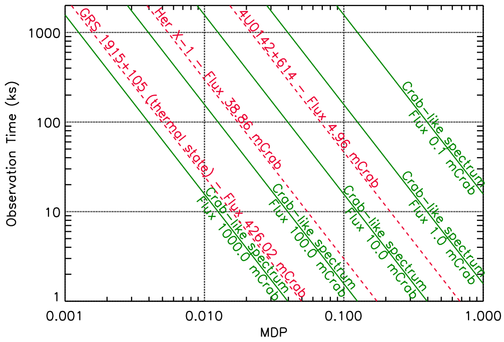

Fig. 2. Observation time required to reach a certain MDP as a function of the flux of the source for PolariX.

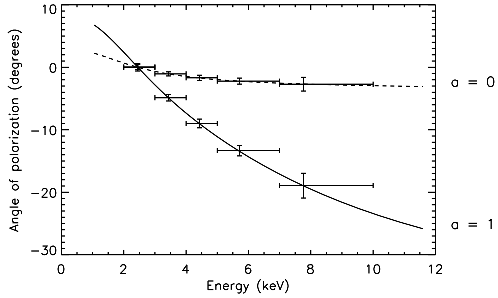

Fig. 3. Simulated 1 Ms observation of GRS 1915+105 with PolariX. The solid and dashed curves refer to the case of a Kerr and a Schwarzschild black hole respectively. Errors are at the 1-σ level (Dovčiak et al. 2008).

tion of the plane of polarization with energy (Connors et al. 1980). This effect was simulated by Dovčiak et al. (2008) and the result is reported in Fig. 3 for a long observation (1 Ms) of the galactic micro-quasar GRS 1915+105. The rotation in the case of Kerr black holes is much larger, since the accretion disk arrives closer to the black hole and the high energy radiation escapes from a stronger gravitational field. A long observation of the molecular cloud Sgr B2 could also prove that our Galaxy was a low luminosity active galactic nucleus only a few hundreds years ago. If Sgr B2 is reflecting a flare by Sgr A* (Sunyaev et al. 1993), its emission should be almost completely polarized and the direction of polarization should point to the center of the Galaxy (Churazov et al. 2002). A 1 Ms observation would set a strong angular constrain on the position of the illuminating source (see Fig. 4

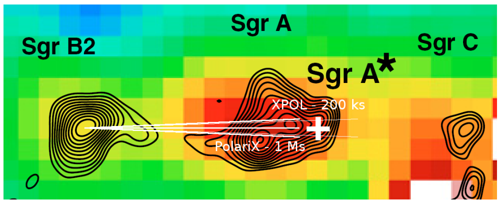

Fig. 4. Monte Carlo simulations of Sgr B2 observation with PolariX and XPOL lasting 1 Ms and 200 ks respectively. A polarization degree of 70% is assumed. Errors are at the 1-σ level (background image from Revnivtsev et al. 2004).

3.2. XPOL on-board IXO

XPOL (*X*-ray *Pol*arimeter) is the photoelectric polarimeter based on the GPD on-board IXO (Costa et al. 2008). The instrument shares the same basic design as the pathfinders (He-DME mixture, energy range between 2-10 keV): the only improvement required is to reduce the dead time of the chip to sustain the rate expected in the focus of the large IXO optics.

IXO is an observatory and only a fraction of time (~10%) is dedicated to X-ray polarimetry. Then the large optics of IXO is in part compensated by the lower observation time. However the goal is to reach a MDP of 1% for 1 mCrab source in 100 ks of observation, with a two orders of magnitude improvement with respect pathfinders. Another scientific driver for XPOL is the long focal length ($f \geq 20$ m). A high angular resolution (5 arcsec) is expected including the effect of the inclined penetration of photons in the gas cell. This is a large improvement which can't be achieved by any pathfinder mission and makes possible the polarimetry of faint sources which must be resolved from close or diffuse emission, like jets or the fine structures of the PWNe (see Fig. 5). For example, we expect to reach a MDP of 6% for the M87 knot A in 200 ks.

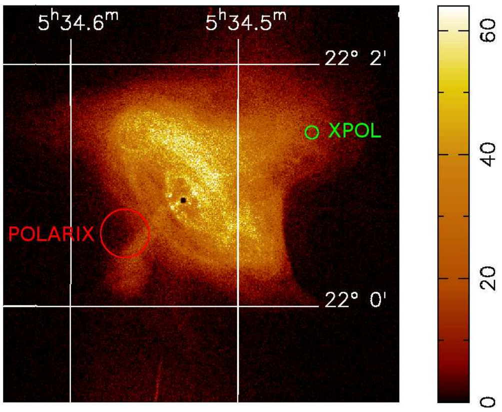

Fig. 5. Comparison of the HEW of PolariX and XPOL (background image from Weisskopf et al. 2000).

4. Conclusions

X-ray polarimetry could soon become real thanks to instruments based on photoelectric effect. In particular, the Gas Pixel Detector has different possibilities and at least one pathfinder mission could be launched in a few years. The sensitivity in this case would allow to detect a polarization higher than 1% for 100 mCrab source in one day of observation. Instead, at the focus of the large telescope of IXO, the goal is to reach a minimum detectable polarization of 1% for 1 mCrab source in one day.

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