An X-ray Polarimeter for HXMT Mission

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ABSTRACT

The development of micropixel gas detectors, capable to image tracks produced in a gas by photoelectrons, makes possible to perform polarimetry of X-ray celestial sources in the focus of grazing incidence X-ray telescopes.

HXMT is a mission by the Chinese Space Agency aimed to survey the Hard X-ray Sky with Phoswich detectors, by exploitation of the direct demodulation technique. Since a fraction of the HXMT time will be spent on dedicated pointing of particular sources, it could host, with moderate additional resources a pair of X-ray telescopes, each with a photoelectric X-ray polarimeter in the focal plane.

We present the design of the telescopes and the focal plane instrumentation and discuss the performance of this instrument to detect the degree and angle of linear polarization of some representative sources.

Notwithstanding the limited resources the proposed instrument can represent a breakthrough in X-ray Polarimetry.

Keywords: X-ray Astronomy, X-ray optics, Polarimetry

1. INTRODUCTION

According to an extended literature X-ray sources are expected to show a significant degree of linear polarization. This can derive from the non-thermal emission process itself or from the transfer of the radiation in subsystems with geometries very far from the spherical symmetry, such as accretion disks or columns. The birefringence of plasma and of vacuum itself in the presence of strong magnetic fields, stated by Quantum Electro Dynamics is the source of an additional phenomenology, as it can, in different conditions, polarize or depolarize the radiation or rotate its polarization plane. As a matter of fact these physical conditions, expected to produce polarization as a function of time or energy, should be present in most of the astrophysical X-ray emitters. The polarization should provide a tight test of any model far below what required by spectra and variability alone. Significant efforts were spent on polarimetry in the early phase of X-ray Astronomy, until the late '70s. A series of rockets by the Columbia University Team first detected the polarization from the Crab Nebula.¹ This result was improved by OSO-8 satellite,² that also derived upper limits on polarization of other sources.^{3,4} In the following 30 years no more polarimeter has been launched aboard a space mission. In fact the introduction of X-ray optics

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increased the sensitivity of X-ray missions of orders of magnitude, in terms of identification and imaging, while the sensitivity of polarimeters, based on the bragg or scattering techniques, was improving very slowly. Moreover Xray telescopes abandoned the requirement of rotating vehicle, while this was still a requirement for polarimeters. In fact polarimetry was perceived as low throughput subtopic, with sensitivity increasingly mismatched with that of these new missions, targeted to different sources and setting though requirements in terms of resources and operations. A dedicated mission could be more suitable but has not been approved so far. A new chance to rejuvenate this subtopics of X-ray astronomy is yielded by the recent development of detectors based on photoelectric effect in gas.⁵ They are truly imaging devices and, when combined with X-ray telescopes permit to extend to polarimetry the same huge increase of sensitivity, achieved so far for imaging and spectroscopy. They also allow for a good timing and a resolution suitable for energy resolved polarimetry of continua. In any case, starting from the data of OSO-8 and taking into account the modern theoretical analysis polarizations to be typically expected from celestial sources are in the range of 1 to a few %. In statistical terms this means that sources are to be observed till photons are detected in numbers of the order of $10^5 - 10^6$. This implies that polarimetry is still confined to a limited number of brighter sources. Therefore three type of mission scenarios can be foreseen: a dedicated mission, a mission with one telescope and different instruments to be alternatively set in the focus, a mission with different instruments in parallel with a reasonable overlap of scientific objectives.

A certain connection does exist between physics of hard X-ray emitters and expectations of polarization. Non thermal processes, can be singled out by the presence of *hard tails* as well as from the existence of linear polarization. The latter also provides a geometric information (e.g. the orientation of magnetic fields or the direction of particle acceleration). Alternatively the presence of hard component and the absence of polarization can provide the evidence for disordered systems (e.g. disordered magnetic fields for synchrotron, or diffuse source of seed photons in an inverse compton). Because of these overlaps and because of a reduced mismatching of observing times, a polarimeter and a hard X-ray instrument can efficiently combine, resulting in a very performing mission for deep Physics of non thermal sources. The Hard X-ray Modulation Telescope mission HXMT,⁶ based on an array of phoswich detectors with slat collimators, is mainly devoted to performing a hard X-ray all-sky imaging survey with both high sensitivity, spatial of 5 arcminutes and positioning accuracy of 1 arcminute. HXMT can also make high signal-to-noise ratio pointing observations of sources of particular scientific interest. HXMT ia now in the full design phase and a candidate for the first Chinese dedicated astronomy satellite. Since a combination of Hard X-ray measurements with polarimetry seems to be very promising, Italian and Chinese Space Agencies are negotiating the possible inclusion in the same bus of two X-ray telescopes, with in the focus two gas pixel polarimeters.

2. THE TELESCOPES

The design of the proposed telescopes is based on the following concepts:

- be compliant with the allocated weight and volume
- be based on solid technologies with some limited improvements for the particular application
- relax some features that cannot be coped by the detector in favor of a larger collecting area

Since the schedule of the Mission is relatively ambitious we selected the technology of producing the telescope shells by replicating superpolished mandrels with electroforming. This technology, developed for SAX⁷ and successfully applied to XMM⁸ and JET-X⁹ (whose spare unit is the optics of SWIFT X-Ray Telescope¹⁰), is adequately under control for a short track mission. A major improvement is the use of Iridium as a reflector. The constraint of a maximum length of 2.5 meters has fixed the mirror focal length to 2.1 meters. The Ir provides an improvement at higher energies. Another improvement of high impact is the addition fa thin Carbonium coating. In fact, taking into account the dependence on the energy of the modulation factor, of the reflectivity of materials and the steepness of the spectra of sources, the sensitivity of the polarimeter is maximal around 2-4 keV. In this range the M edges of Ir (but Au would not be better) introduce a strong decrease of reflectivity. It has been proofed that a thin Carbonium coating can significantly reduce the effect.¹¹ This treatment is very important in general, but is particularly effective if the telescope is used for polarimetry.

The gas pixel detector has an intrinsic resolution of the order of 150 μ m, but in the focus of a telescope photons impinge inclined on the gas cell. With an absorption gap of 10 mm the uncertainty on the depth of the interaction results in a further blurring of the order of 400 μ m. For this relatively short focal length this additional effect limits the angular resolution to ~ 40 arc seconds. For this reason and thanks to an improved design to reduce the tension at the interface with the mounting structure, we assume that a thickness of 100 μ m for the shells is sufficient. The total weight of the 30 shells is 10.5 kg. In fig. 1 we show the drawing of the mirror package, the focal plane and the carbon fibre supporting structure. Shells are mounted, as usual, with spiders. Since the detector is sensitive only above 1.5 keV we can afford a thermal shield in the front and can avoid the heavy and long collimator/buffle in front of the mirrors.



Figure 1. The telescope

In fig. 2 we show the effective area of one telescope, with and without the coating of carbon. The introduction of the latter is very effective indeed. The reduction due to the spider is already accounted.

Table 1. Features of Each Telescope	
Shell Design	Wolter 1
Shell Length	$30~{ m cm}$ $ imes$ 2
Focal Length	2.1 m
Number of Shells	30
Shell Thickness	$100 \ \mu \mathrm{m}$
Coating	Ir + C (only 22external)
Mounting	spider
Weight of shells	$8.1 \mathrm{~kg}$
Total Weight	$41.4 \mathrm{~kg}$

3. THE FOCAL PLANE

In the focus of each telescope there is a gas pixel detector. This device has been developed by the Pisa INFN team. It is based on the imaging of the tracks of photoelectrons created by conversion of X-ray photons in a low Z gas mixture. The electrons of the track are drifted by an electric field to a Gas Electron multiplier that multiplies them in a proportional manner, while preserving the shape of the track. The amplified electrons are collected by metal pads, close to the GEM, that are on the top layer of a VLSI chip, that includes, below the projection of the pad, a complete and independent electronic chain. From the analysis of the charge collected on each pad an image of the track is obtained and the interaction point of the photon and the initial direction



Focal length = 2.1 m, 30 shells, D = 9-27 cm, weights (l/h) = 10.5 / 20.4 kg (including 30% structure)

Figure 2. The effective area of one telescope

of the photoelectron are estimated. The most recent implementation of the VLSI chip has ~ 100000 pixel with a pitch of 50 μ m on an hexagonal pattern.¹² The chip has self-triggering capability and fetches to the output only the content of a Region of Interest around pixels that triggered. Sealed prototypes of it, with a Beryllium window 50 μ m thick, have been recently developed and manufactured a nd show a good stability versus time and radiation.¹³ In fig. 3 we show a prototype of sealed detectors. In fig. 4 we show two examples of tracks produced on the detector by photons from an X-ray generator with Cr anode. Various mixtures have been tested. The most performing with a band pass like that of HXMT telescope is presently a mixture of He (20%) and DME (80%), which is the current baseline.

The detector is connected with a flexible cable to an interface electronics performing the A/D conversion and routing the controls to the VLSI chip. Beside the detector and the interface electronics the focal plane includes a filter wheel to allow to cover the window, for protection, or to position in front of it a polarized¹⁴ or an unpolarized calibration source. Also a long buffle has been included to prevent stray light and ions that could arrive to the window. The whole is shown in fig. 5.

The control electronics including High Voltage Power Supplies, DC-DC converters, PDHU, Mass Memory, houskeeping and interface to telemetry, is located separately from the telescope.

While the requirements for the detector and the electronics are very moderate in terms of power and weight a large amount of information must be transmitted. In fact the excellent noise figure of the ASIC chip (50 electrons ENC^{12}), allows, with a gain of ~ 500 from the GEM, for the detection of single electrons generated in the gas. This, combined with the pitch of 50 μ m for the pixels, gives the capability to preserve very detailed information on the track, but requires an adequate amount of bit. Photons of 2 keV generate tracks with, in average, 40 pixels with charge content above zero. This number increases to 87 for photons of 6 keV. With the foreseen telescopes and detectors we expect from the Crab 266 counts/s, corresponding to around 250 kbit/s, after zero suppression. This number can be reduced by means of various compression techniques. The most radical would be an analysis of the track onboard, that would reduce the rate to ~ 16 kbit/s.



Figure 3. A prototype of sealed micropixel detector



Figure 4. Two examples of photoelectron tracks as visualized by the micropixel detector



Figure 5. The focal plane

4. THE EXPECTED PERFORMANCES

In table 2 we resume the main overall features of the proposed instruments

 Table 2. Overall Features of the proposed instrument (two telescopes)

Effective Area @ 3 keV	740 cm^{-2}
f.o.v.	$22' \times 22'$
Window	$50 \mu m$ Beryllium
Gas filling	DME (80%) He (20%)
Gas Pressure	$1 \mathrm{atm}$
Absorption gap	$10 \mathrm{mm}$
Angular Resolution	1'
Energy Resolution	$\frac{\Delta E}{E} = 0.2 \times (6/E)^{0.5}$
Energy Band	1.5 - 10 keV
Timing	$10 \ \mu s$

4.1 The statistics

The sensitivity to sources is usually expressed as:

$$MDP = \frac{4.29}{\mu\epsilon F} \times \sqrt{\frac{B + \varepsilon F}{ST}} \tag{1}$$

Where MDP is the Minimum Detectable Polarization at 99% confidence, μ is the modulation factor, ϵ is the efficiency, S is the flux from the source, B is the background per unit of area and T is the observing time.

In the case of HXMT the background is negligible to any practical effect. The modulation factor has been computed by Monte Carlo simulations, which have been recently confirmed by laboratory testing with polarized, monochromatic sources at energies of 2.6, 3.7 and 5.2 KeV^{15} . We can therefore compute MDP for some sources peculiar or representative of various classes. The results are shown in fig. 6.



Figure 6. The Minimum Detectable Polarization for observations of 10^5 or 10^6 seconds with HXMT

One day of observation can be sufficient to study bright galactic sources, such as Cyg-X3, GRS1915+105 or 4U1700-37. With a few days of observation phase resolved polarimetry of Her X-1 or Vela X-1 could be performed to a few % level, allowing for a direct measurement of the inclination of the magnetic axis with respect to the rotation axis and to the sky: a breakthrough for the detailed modelling of these systems. A few bright extragalactic sources could be detected with one week pointing. Also relatively faint sources like Circinus Galaxy or 3C279 could be observed, since high degrees of polarization can be expected. But in the following we want to propose two cases of particular interest.

4.2 The sensitivity to the angle: the case Cyg-X1

In an accretion disk the polarization, produced by scattering on selected directions, will be always perpendicular or parallel to the disk. In the low energy case Chandrasekhar¹⁶ has demonstrated that polarization cannot exceed the limit of 11.7 %. Sunyaev and Thitarchiuck¹⁷ have demonstrated that in the X-ray band, when the energy of the scattered photons can be higher than that of the source photons, due to inverse Compton, the polarization can significantly exceed the Chandrasekhar limit. But, as outlined by Connors, Stark and Piran,¹⁸ another effect will be present as well. The X rays will be parallel or perpendicular to the disk in the rest frame, but in the travel to the observer, will experience the strong gravitational field of the Black Hole, that in the observer frame will result in a rotation of the polarization plane. Since the photons of different energies will derive from regions of the disk at different distance from the BH, the total result will be a rotation of the polarization plane as a continuous function of the energy, a unique signature of the presence of a Black Hole. In fig. 7 we show the capability of HXMT to detect this effect if a polarization of 1% is there. This is conservative. If the polarization

is higher, as suggested by a marginal detection with $OSO-8^4$ the polarimeter will allow for the discrimination between a Schwarzschild BH and a Kerr BH.



Figure 7. The Rotation of the polarization angle for Cyg-X1. The two curves represent the two extreme cases of a Schwarzschild BH and a Kerr BH

4.3 The sensitivity to the angle: the case of Sgr B2

The center of our Galaxy harbors a 2.6×10^6 solar masses Black Hole. The Black Hole is very quiet, its accretion luminosity being about 10 orders of magnitude lower than the Eddington luminosity. This inactivity is shared by most of supermassive BH at the center of galaxies. only a small fraction are very active and there is evidence of turning from one state to the other. But at the projected distance of about 100 pc from the Black Hole, there is a giant molecular cloud, Sgr B2(Fig. 8(b)), which in X-rays has a pure reflection spectrum^{19,20}). However, it is not clear what Sgr B2 is reflecting: there are no bright enough sources in the vicinity. The simplest explanation is that a few hundreds years ago our own Galactic Center was much brighter, at the level of a low luminosity Active Galaxy: the molecular cloud would then simply echoing the past activity (,²¹¹⁹). If this is true, as shown in Fig. 8(a), the reflected X-rays should be highly polarized: the degree will depend on the angle ϑ and for $\theta=0$ will be of 100% for the continuum (the fluorescence will be unpolarized in any case). From the polarization we can derive θ and from that the distance of the source and the time when our own galaxy was a little AGN.²² Moreover the perpendicular to the polarization plane will *point* to the source of the reflected photons. For a polarization of $\geq 70\%$ (that corresponds to angles from 60 to 120 ° the error on the angle will be lower than 3° and the association of the Sgr B2 with the BH will be very cogent as shown in fig. 8(b). Of course if ϑ is far from 90° the error would be larger.

5. CONCLUSION

The two telescopes proposed for HXMT, based on established technologies, can perform polarimetry on several classes of objects and would boost this subtopics of X-ray astronomy, so far exploited only marginally.



Figure 8. If the X-rays from SgrB2 are coming from SgrA and are reflected toward us, the amount of polarization will depend on the angle ϑ . From the measurement we can determine ϑ and thence the distance to us. If the hypothesis is correct the cone of confidence will include the source of the scattered photons and make the association between the two sources much stronger than from spectral arguments. The precision on the angle will depend on the degree of polarization. We superimpose to the IBIS map²⁰ the cases of 70% and 10% polarization

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