OPENING A NEW WINDOW TO FUNDAMENTAL PHYSICS AND ASTROPHYSICS: X-RAY POLARIMETRY

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Abstract

An extensive theoretical literature predicts that X-ray Polarimetry can directly determine relevant physical and geometrical parameters of astrophysical sources, and discriminate between models further than allowed by spectral and timing data only. X-ray Polarimetry can also provide tests of Fundamental Physics.

A high sensitivity polarimeter in the focal plane of a New Generation X-ray telescope could open this new window in the High Energy Sky.

1. Introduction

Since the birth of X-ray astronomy, spatial, spectral and timing observations have improved dramatically in quantity and quality, providing a wealth of information on almost all classes of cosmic objects. One key aspect of the emission, however, remained basically unprobed: polarization. Conventional polarimeters are cumbersome and poorly sensitive, so that they were not included in the major missions.

The lack of polarimetric measurements is extremely painful, as they would add two essential parameters (amount and angle of polarization) to those already derived from spectra and timing, providing unique information on the Geometry and Physics of sources belonging to most of classes of interest (Meszaros et al. 1988).

The advent of new generation, focal plane, photoelectric polarimeters (Costa et al. 2001, Bellazzini et al. 2003), all developed in Europe, provides the breakthrough in sensitivity needed to search for polarization degrees of astrophysical interest (a few percent) in several classes of cosmic sources. We discuss here briefly a few scientific cases of outstanding interest.

2. What can Polarimetry Test?

2.1. Astrophysics

Polarization from celestial sources may derive from:

– Emission processes themselves: cyclotron, synchrotron, non-thermal bremmstrahlung (Westfold 1959, Gnedin & Sunyaev 1974, Rees 1975)
– Scattering on aspheric accreting plasmas: disks, blobs, columns. Resonant scattering of lines in hot plasmas (Rees 1975, Sunyaev et Titarchuk 1985, Meszaros et al. 1988, Sazonov et al. 2002).
– Vacuum polarization and birefringence through extreme magnetic fields (Gnedin et al. 1978; Ventura, 1979; Meszaros et al. 1980)

All these processes produce relevant polarization that, unless averaged and smeared by a symmetric distribution of the involved regions, will be detectable in a variety of situations and classes of sources:

– ordered acceleration
– accretion
– reflection present or past (archaeoastronomy)
– jets

2.2. Fundamental Physics

– Matter in extreme magnetic fields
– Matter in strong gravity fields
– Long Distance Quantum Gravity effects

2.3. Big Hopes Meagre Results

Notwithstanding these big expectations, polarimetry, one key aspect of the emission, has remained basically unexplored. After some pioneering rocket experiment, two polarimeters have been flown aboard ARIEL-5 and OSO-8. So far, only one detection, the Crab Nebula, (Novick et al. 1972, Weisskopf et al. 1976, Weisskopf et al. 1978) and a handful of not very significant upper limits (Silver et al. 1978, Hughes et al. 1984) are available, all of them obtained with the Bragg Polarimeter on-board OSO-8. The results of Polarimetry are indeed marginal in X-ray Astronomy.

2.4. The Technique is the limit

The technique conventionally exploited to measure linear polarization is bragg diffraction at 45°. The whole instrument is rotated around the axis and the modulation of the diffracted flux at each angle provides the amount of polarization. Due to the narrow band of the process, there is a good control of systematics and imaging is preserved, but, even with the best mosaic crystals, the integrated efficiency is extremely low.

The other conventional technique is Compton scattering around 90°. The technique is more effective, but only above 5 keV, is not imaging, heavily dominated by background and affected by systematics.

Both techniques require rotation around the optical axis, are relatively cumbersome and yield a low sensitivity.

3. A new device: the Micropattern Gas Chamber

A new device that analyzes linear polarization, while preserving the information on the point of impact, the energy and the time, is now available: the Micropattern Gas Chamber. It represented, at the beginning, the extreme evolution of the imaging proportional counter, with a planar multiplication stage and a multi-anode read-out. Now it evolved into a full pixel detector, with a gas converter. The X-ray photon is absorbed in a low Z mixture, producing a photoelectron that ionizes the gas. The result is a ionization track. Electrons drift to a Gas Electron Multiplier, are multiplied and collected from a read-out plane, made of metal pads, each with its individual electronic chain (Fig. 1). From the analysis of the track image (see Fig. 2), the interaction point and the photoelectron direction are reconstructed. The angular distribution of the photoelectron directions depends on linear polarization with a cos^2 distribution.

In a first pioneering phase the read-out was based on a multi-layer PCB routing the signals of each pad to an external analysis chain, resident on an ASIC chip. In a further stage a VLSI chip was developed including the metal pads acting as an anode and a complete electronic chain under the projection of each pad, in lower layers(Fig. 3). On trigger from the GEM signals are routed to an external ADC. The whole is extremely compact and allowed for a fast development of chips of increased dimension (Fig. 4) with a progressively decreasing pixel size (see Table 1). The last generation chip arrived to 100000 pixels of 50μm pitch. To reduce the read-out dead time the new chip is capable to self trigger and fetch only a window around the trigger pixel.

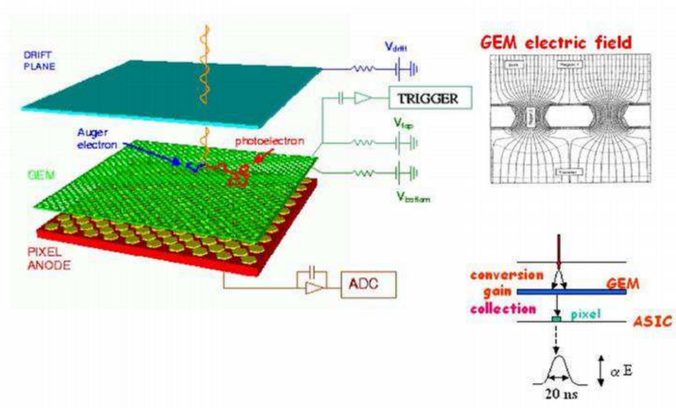

Figure 1. The Concept of Micropattern Gas Chamber

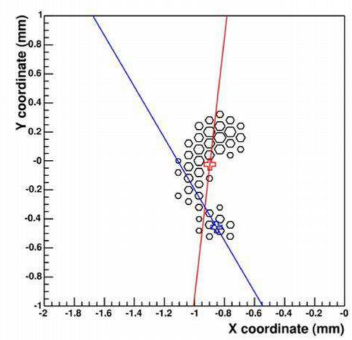

Figure 2. The track produced in the gas by a 5.9 keV photon is recorded by the MPGC and analyzed with the following sequence: barycenter evaluation; reconstruction of the principal axis; reconstruction of the conversion point; reconstruction of emission direction. The polarization is derived from the reconstructed angular distribution of the photoelectrons.

This new device in the focal plane of a New Generation X-Ray Telescope with an effective area $\geq 10m^2$ can turn the dream of X-ray Polarimetry into reality. The critical parts (GEM and VLSI) do exist: body, window, gas handling, HV etc. are conventional, well established technology. It is relatively small and compact: no cryogenics, no rotations and the VLSI is radiation hard. It is very fast: can handle high rates ($5{\times}10^4$ c/s). It is position sensitive to around 100 μ m: oversamples the p.s.f. of any optics but Chandra. While doing Polarimetry also performs timing, imaging (Fig. 5) and spectra (with the energy resolution of a good PC).

We tested the device searching for systematic effects, namely spurious polarization, when measuring photons from an unpolarized (fluorescence) source. We do not find

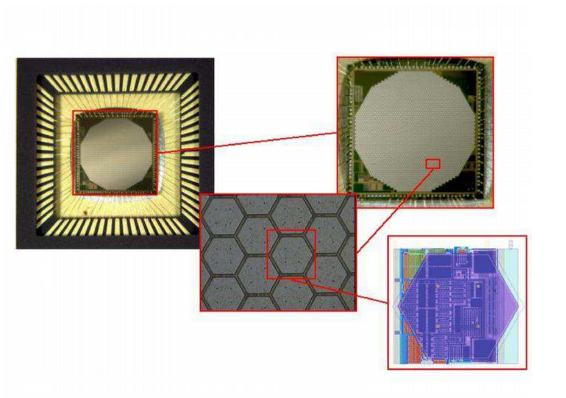

Figure 3. Progressively zoomed photos of the Chip of generation I (2100 pixel) showing the pad structure. The last zooming shows the drawing of the read out electronics for a single pixel harbored in silicon layers below the pad.

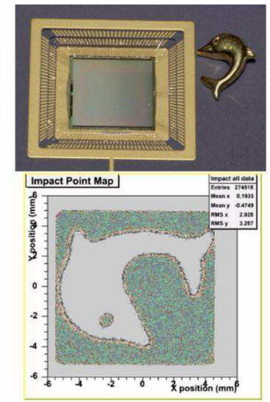

Figure 5. Image of an ear ring done with a detector based on chip of generation II and processed with the reconstruction of the impact point

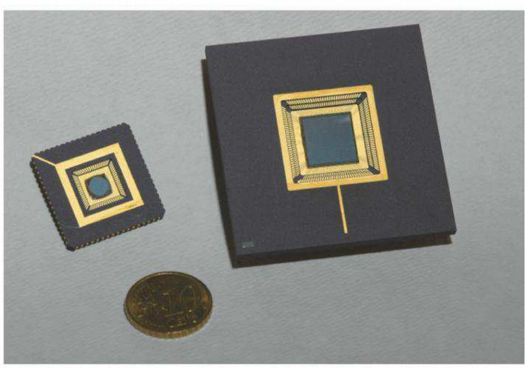

Figure 4. VLSI read-out chips of generation I(2100)pixels and II (20000 pixels)

Table 1. The evolution of the read-out from the first prototype, based on ML PCB technique, to the ASIC chips.

Device	Epoch	pixels	pixel(μm)	size (mm)
Protype PCB	2001	500	120	3 diam
Chip I	2003	2100	80	4 diam
Chip II	2004	20000	80	11 x 11
Chp III	in prod.	100000	50	17 x 17

any effect down to 0.2% , so that this is our present limit, to be possibly improved.

4. Which Polarimetry with this new device?

4.1. The strange case of Sgr B2

Interaction of Supermassive Black Holes and their host galaxy is a clue of High Energy Astrophysics in the Cosmic Vision Era. Most of supermassive BH at the center of galaxies are nowadays inactive. A few are very active. How do they swap from one status to the other? A noticeable case: our own Galaxy. The discovery of a 2.6×10^6 solar masses Black Hole at the center of our own Galaxy was certainly one of the most exciting result in Astronomy in recent years. The Black Hole is very quiet, its accretion luminosity being about 10 orders of magnitude lower than the Eddington luminosity. However, if Brahe or Galileo could have at their disposal a X-ray satellite, they would possibly have observed the Galactic Center as the brightest extrasolar X-ray source. In fact, at the projected distance of about 100 pc from the Black Hole, there is a giant molecular cloud, Sgr B2(Fig. 6), which in X-rays has a pure reflection spectrum (Fig. 7, Koyama et al. 1996). 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 (Sunyaev et al. 1993, Koyama et al. 1996). Polarimetric measurements would be able to confirm or disproof this hypothesis beyond doubts (Churazov et al. 2002): not only reflected radiation should be highly polarized, but the polarization angle must be perpendicular to the projected line connecting the Black Hole to Sgr B2. The degree of polarization will also tell us the true distance of Sgr B2 (Fig. 8), much tightly constraining the time at which the Galactic Center was active.

4.2. Matter under extreme magnetic fields

Magnetized neutron stars are an excellent laboratory to test QED effects in the presence of magnetic fields that cannot be produced in laboratories. These span from the well established fields of $10^{12}-10^{13}$ gauss of accreting X-ray pulsators to the extreme fields up to 10^{15} gauss proposed for Soft Gamma Repeaters and Anomalous X-ray Pulsars.

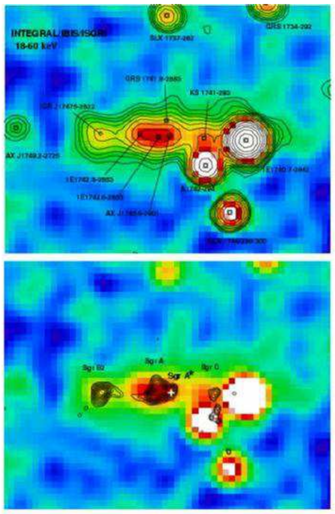

Figure 6. The Galactic Center as imaged with INTEGRAL-IBIS experiment

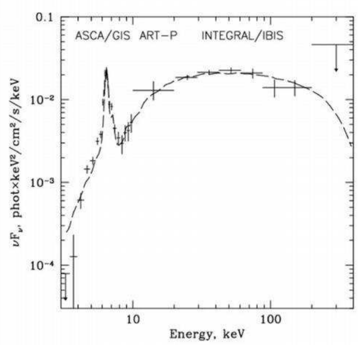

Figure 7. The Spectrum of SgrB2 by combining data from ASCA and IBIS is a pure reflection spectrum. The input spectrum corresponds to a power law with photon index 1.8.

In **isolated neutron stars**a soft thermal emission is produced in hot spots at the surface of the star or close to it. This is a detected as a black-body emission smoothly modulated by the rotation of the star. The radiation to arrive to the observer will cross a region of vacuum with strong magnetic field, whose intensity and orientation will be phase dependent. But QED predicts a significant birefringence of the vacuum that will not affect the continuum energy spectrum, but will introduce a very strong, phase dependent, polarization, allowing to map the geometry and intensity of the magnetic field (Pavlov et Zavlin 1978, Heyl et Shaviv 2002, Lai et Ho 2003). Isolated X-ray pulsars are too faint and too soft to make this measurement feasible with the present status of the MPGC technology, but could become realistic with an improved detector. Anyhow the same phenomenology is expected (and should be even more outstanding) in the case of Soft Gamma Repeaters. The flux of SGRs, even in quiescent state, is compatible with such a measurement. Due to the extreme magnetic field also two absorption features should be present, one at the so called vacuum resonance frequency, and one at the proton-cyclotron resonance (Niemiec et Bulik 2005). These features should have different phenomenology with respect to polarization. This would provide a direct evidence of the presence of extreme magnetic fields and provide a check of the magnetar model, so far mainly supported by energetic considerations. In an active phase or in the first few days following a major emission episode the situation may become even more interesting, because of the likely presence of a transient ionized atmosphere. In this frame it would be extremely attractive a measurement of the lines such as the one detected at 5.0 keV in the spectrum of SGR1806-20 (Ibrahim et al. 2002). It has been suggested (Zane et al. 2001) that, this feature are proton cyclotron in the presence of a magnetic field of 1.0 $\times 10^{15}$ gauss. This completely exotic scenario can be deeply probed with polarimetry. In fact the energy resolved evolution of the polarization amount and angle following a burst episode will provide a true laboratory to test QED prediction and to investigate the nature of the delayed emission of magnetar. A negative result would push toward other interpretations, such as the presence of red-shifted Fe lines, that would be, conversely, of the highest interest for the EOS of Neutron Stars.

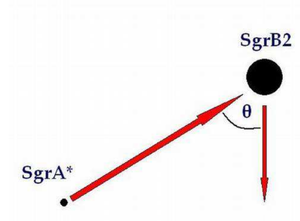

Figure 8. We only observe a projected distance of 100pc from SgrA and SgrB2. The amount of polarization will provide the angle ϑ and, fix the distance of the two sources and thence give the epoch when our GC was an AGN

Accreting Magnetic Neutron Stars are probably the best known objects of X-ray Astronomy. But, while the mass can be derived from the dynamics of the binary system, the rotation period is derived from the pulsation and the magnetic field can be measured with the cyclotron resonance energy, the mechanism of transfer of plasma to the poles of the star is still derived through complex models that fit the pulses shape and spectra. These leave the geometric parameters (inclination of the magnetic field versus the rotation, projection of the rotation axis on the sky) as free parameters to be determined with the fit. As demonstrated by (Meszaros et al. 1988), in such a system polarization is modulated and the swing of the polarization angle with phase directly measure the orientation of the rotation axis on the sky and the inclination of the magnetic field: in Fig 9 the case 45°, 45°. The same data will also identify the emission model. In a fan beam the polarization will be correlated in phase with the luminosity, while in a pencil beam it will be anti-correlated.

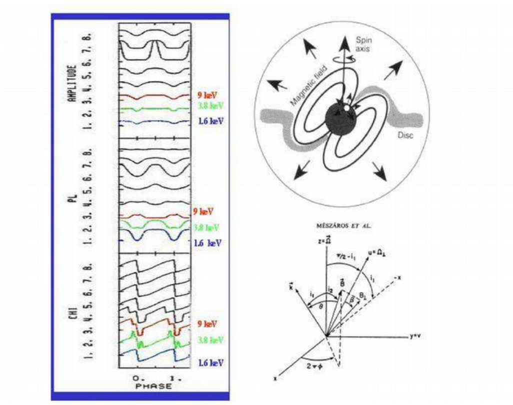

Figure 9. The luminosity, polarization amount and polarization angle for an X-ray pulsator at different energies and phases give a direct measurement of the major geometric parameters.

Millisecond accreting pulsar represent a case of particular interest. Millisecond coherent oscillation were discovered in a number of low-mass X-ray binaries. The spectrum is represented by the sum of a black-body like emission and a Comptonized tail. If the Comptonization is produced in the radiative shock at the antipodal accretion sites close to the neutron star surface, we expect (Viironen et Poutanen 2004) that the pulse profile of the scattered radiation be phase-depedent polarized. The amplitude of polarization degree and angular phase depend on the geometry but also on the neutron star compactness. However Flux and polarization will always be in phase. If instead is the disk that intercept the flux from the antipodal spot (Sasonov et Sunyaev 2001) Doppler boost will make polarized flux trail or lead the primary pulse of the direct emission. In both cases polarimetry would probe the regions close to the surface of the neutron star and complement timing and spectroscopy to the study of the Equation of State of Neutron Stars.

4.3. Matter under extreme gravitational fields

Polarization from celestial sources may derive from photons emitted in the innermost regions of an accretion disc around a neutron star or a Black Hole which have, for symmetry reasons, a polarization vector which, in the matter reference frame, is either parallel or perpendicular to the disc axis. To the distant observer, however, the polarization angle appears rotated due to the parallel transport of the polarization vector along the geodesics. This effect is significant only in the strong gravity field regime, and the rotation is of course larger the closer to the Black Hole the photon is emitted. In Galactic Black Hole systems in the so–called 'soft states', X-rays may be dominated by thermal emission from the disc, which may be polarized due to Thomson scattering in a hot surface layer. The decrease of the disc temperature with radius implies that higher energy photons suffers a larger rotation than softer photons, implying an energy dependence of the rotation of the polarization angle. This very clear phenomenology was predicted several years ago (Stark & Connors 1977, Connors, Stark, & Piran 1980). The predicted rotation with energy is shown in Fig 10, but has never been verified due to the lack of the proper polarimeter.

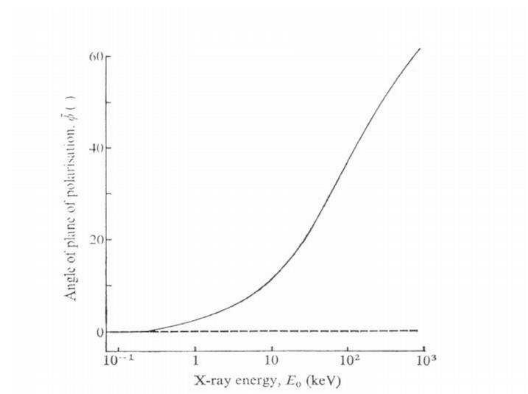

Figure 10. The energy–dependent rotation of the polarization angle for Cyg X-1 due to General Relativity effects (Stark & Connors 1977)

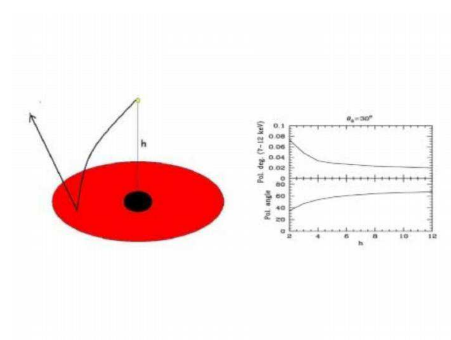

Figure 11. The degree and angle of polarization of the reflected radiation (right panel) as a function of the height of the primary source, assumed for simplicity to be a point on the Black Hole axis (left panel). Such a simple geometry seems able to explain the otherwise puzzling variability of the relativistic iron line in MCG-6-30-15 (Miniutti et al. 2003).

In Active Galactic Nuclei, where thermal emission peaks in the UV band, the disc reflects (and polarizes) via Compton scattering part of the primary X-ray emission. The primary emitting region is likely variable, with consequent variations of the regions of the disc most illuminated. As a result, a time variation of the polarization angle is expected. The gravitational bending has been claimed to explain the different variability of relativistic broadened line and continuum in MCG-6-30-15 (Miniutti et al. 2003), Variability of polarization angle with time can proof or disproof this model (Dovciak et al. 2004) or, more in general, any scenario in which reflection originates in the innermost regions of disc, and complement data from spectroscopy of relativistic lines. The results in Fig. 11 have been obtained assuming unpolarized primary emission, a rather conservative assumption. Because the primary emission is likely due to Comptonization, it is also expected to be significantly polarized (Haardt et Matt 1993, Poutanen et Vilhu 1993); the net polarization degree is then likely to be larger, still maintining time variations of the polarization angle, as primary flux variations are likely related to variations in the geometry of the emitting region.

Whatever the details, it is hard to imagine other effects producing energy and/or time variations of the polarization angles. Thence, if observed, the rotation would provide a strong signature of General Relativity effects, and a test of this theory in regimes that can not be probed within the solar system.

4.4. Cosmic Accelerators

Acceleration of particles is the clue of Cosmic Ray Physics. Super Nova Remnants (both plerionic and shell-like) are the best candidates for acceleration of electrons. They emit up to TeV energies. Jets in AGNs and in Galactic Sources GRBs and their Afterglows are for sure the site of acceleration but the structure and origin of the magnetic field and the structure and energy distribution of jets are still open questions.

4.4.1. Cosmic Accelerators by themselves

The prototype of all cosmic accelerators, the Crab, is also the only source for which X-ray polarization has been actually measured. In 1978 OSO-8 satellite measured a polarization of 19.2 ± 1.0 % (Weisskopf et al. 1978). But this data only refer to the average properties of the system. In Fig. 12 we show the image of Crab from Chandra (Weisskopf et al. 2000), showing that several well distinguished subsystems contribute to the emission,including an inner torus, an outer torus, the pulsar and two polar jets. We also show the f.o.v. of XPOL and the size of a pixel: XPOL can resolve each of these structures and measure the coupling of the magnetic field with accelerated electrons. A major contribution to understanding the acceleration processes in SNR is coming from spectra. The presence of a hard component (extending up to TeV) provides the evidence for acceleration even in shell like remnants. These measurements could be complemented with X-ray Polarimetry, providing, with a much better angular resolution, the degree of order of the particles and the

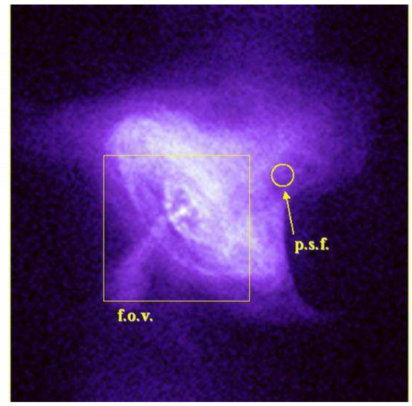

Figure 12. Crab Nebula and pulsar as imaged by Chandra, superimposed the f.o.v. and the p.s.f. of XPOL.

role of turbulence. The angular resolved measurement of the polarization angle provides an information on the geometry of the shocked site, which cannot be derived from spectra.

4.4.2. Cosmic Accelerators to test Quantum Gravity

Quantum Gravity should be effective on the Planck Energy scale (E_{QG}=10^{19} GeV). But the hypothesized existence of space-time foam can produce detectable effects on radiation propagating on very long distance scale. One of the major approach to quantization of Gravity is the Loop QG that predicts birefringence effects. The result is a difference of light velocity for the two states of circular polarization:

$$v_+ = c[1 + \chi(E/E_{QG})^n] \quad (1)$$

$$v_- = c[1 - \chi(E/E_{QG})^n] \quad (2)$$

Since linear polarization is a superposition of the two eigenstates of circular polarization, the plane of linear polarization is subject to a rotation along the path. This birefringent behavior is energy dependent. The index n is different in different models. The linear dependence of the velocity on (E/E_{QG}) (n=1) is already ruled out by the 1976 measurement of X-ray polarization of Crab, already mentioned as the only positive result of X-ray polarization so far (Kaaret 2003).

But the quadratic case is still viable. Following Mitrofanov 2003, the expected rotation is:

$$\Delta\phi \simeq \chi \cdot (D/hc) \cdot E^3/E_{QG}^2 \simeq 10^{-22} \cdot \chi \cdot (E/10keV)^3 \cdot D(3)$$

It requires very large distances to be tested . The effect is larger at higher energies. In high energy γ-rays polarimetry is in principle viable, but is not foreseen in practice. Scattering polarimetry in soft γ-rays is possible, but requires high fluxes and high polarizations for a detection. X-rays are, therefore, the highest energy band where sensitive polarimetry of remote sources can be performed. If a source is emitting mainly for synchrotron the polarization angle should be the same at different energies. Any class of sources dominated by synchrotron can be a good candidate. Of course, to confirm that this study is feasible, objects of the selected class should have been deeply tested and their phenomenology well understood.

Gamma Ray Burst afterglows are a good candidate, because can be studied up to Z=4, but we do not really know how polarized they are (a few % in the optical emission) and the polarization could be variable on short timescales. The observation of afterglows should be performed in an early phase, before they are too faint to be measured. This requires a dedicated strategy of satellite operations. Blazars are likely a good alternative. Even though blazars that can be arrived are closer they should be highly polarized and the dependence on energy should be moderate or null in the X-Rays, as far as we observe the part of the spectrum where synchrotron is largely dominant, or where SSC is well established (Poutanen 1994, Celotti et Matt 1994). The joint variability at different energies, in flaring episodes, suggests that photons come from the same region and, for dominant synchrotron, could have the same polarization angle. So the method could be extended to a larger energy band. QSOs are less attractive, because of the above mentioned effects of gravitational bending. Seyfert-2 galaxies could, conversely, be a candidate class of objects.

5. A polarimeter for a NGXT

Some of the mentioned phenomena could be studied with a photoelectric polarimeter in the focus of a large area telescope, foreseen for a New Generation X-ray Telescope in the frame of the ESA Cosmic Vision 2015-2025. We call this instrument **XPOL**. It is based on two new, but existing, technologies: the GEM and the VLSI read-out. The baseline filling would be a 50% mixture of Ne and DME at 1 Atm pressure. We did all the estimations of sensitivity with this mixture, but there is a margin of improvement, with mixtures and pressures, better tuned with the band-pass of the telescope. The other components (the Be window, the gas cell, the field forming rings) are established technology for proportional counters. The read-out electronics would be relatively simple, as the ASIC chip already performs a pre-selection of the window around the track. Data of faint sources can be directly downloaded. Data from the brightest sources should be recorded on-board, preprocessed and downloaded in a compressed form. Including HVPS, control electronics and a buffle, to exclude the X-ray sky, the needed resources are of the order of 10 kg and 15 watts.

In Fig. 13 we show the drawing of a detector based on these concepts.

In Fig. 14 we show the **sensitivity** of XPOL for different exposure times and for a few representative sources. With observations of one day we can measure the polarization of several AGNs down to % level. Most of objectives outlined in this paper can be achieved with shorter pointing. The impact of systematics shown in the figure refers to the detector. With bright galactic sources this limit is arrived in 10^3 s. Therefore, for these sources, phase or energy resolved polarimetry can be performed in a few hours.

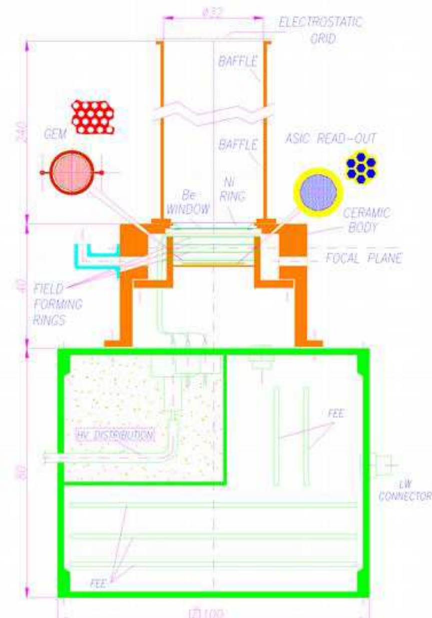

Figure 13. Drawing of XPOL

6. Conclusions

- X-ray Polarimetry complements other techniques for deep physics of extreme objects
- X-ray Polarimetry is now feasible
- X-ray Polarimetry needs a large optics but only small resources in a shared focal plane
- X-ray Polarimetry is worthwhile and should be part of a Cosmic Vision 2020

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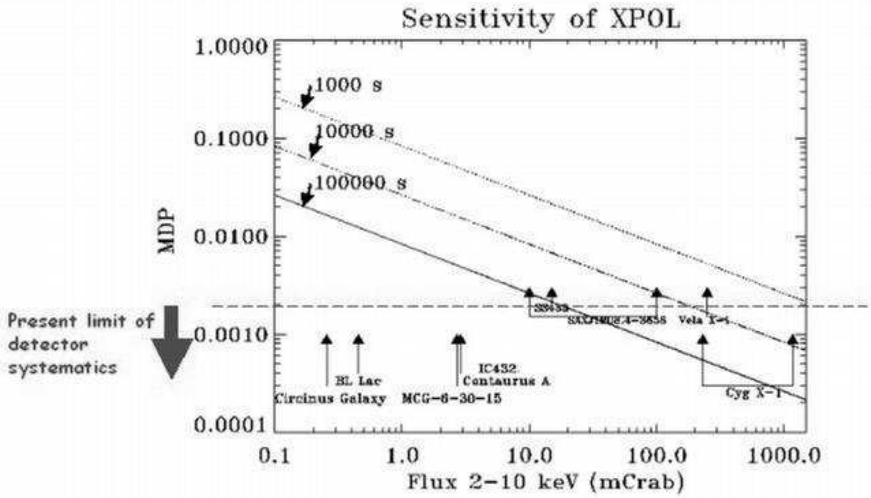

Figure 14. Minimum Polarization Detectable by XPOL on a few representative sources

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