

XPOL: a photoelectric polarimeter onboard XEUS

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ABSTRACT

The XEUS mission incorporates two satellites: the Mirror Spacecraft with 5 m² of collecting area at 1 keV and 2 m² at 7 keV, and an imaging resolution of 5" HEW and the Payload Spacecraft which carries the focal plane instrumentation. XEUS was submitted to ESA Cosmic Vision and was selected for an advanced study as a large mission. The baseline design includes XPOL, a polarimeter based on the photoelectric effect, that takes advantage of the large effective area which permits the study of the faint sources and of the long focal length, resulting in a very good spatial resolution, which allows the study of spatial features in extended sources. We show how, with XEUS, Polarimetry becomes an efficient tool at disposition of the Astronomical community.

Keywords: X-ray Astronomy, polarization

1. INTRODUCTION

XEUS is an ambitious mission planned to be flown ~55 years after the start of X-ray astronomy. XEUS focal plane instrumentation is extremely evolved, especially in the domain of imaging non-dispersive spectroscopy and of wide field imaging with a good spectral response. This follows an almost continuous development from the first rockets through very successful missions such as Einstein, ROSAT, ASCA, SAX, Chandra, XMM. The development of polarimeters has not proceeded in parallel. In fact after the first attempts and the first success with OSO-8, no polarimeter has been embarked aboard a mission, with the exception of SPECTRUM-X-Gamma, that never arrived to the launch. Polarimetry is therefore an all to dig field, and a relatively extended literature (at least compared with the shortage of data) suggests that the crop would be highly rewarding. Nowadays new polarimeters based on the photoelectric effects are available. The INFN of Pisa has developed the Gas Pixel Detector, in the frame of a collaboration with IASF.¹⁻³ These devices combine the capability to measure the polarization with good imaging and can be employed as focal plane detectors, allowing for the same dramatic improvement occurred for imaging with the arrival of Einstein mission. We remind that Einstein was a step forward also from the point of view of satellite attitude. In the pioneering satellites, stabilized on one axis, the detectors had a slit collimator misaligned with respect to rotation. A source was detected as an excess of counts following the collimator profile. Einstein and all the following satellites were stabilized on three axis and a source was a cluster of events in the image consistent with the telescope psf. The diffraction polarimeter is non-dispersive and requires rotation (both of analyzer and of detector) to perform the measurement. The scattering polarimeter is intrinsically non-dispersive but requires the rotation of the whole to compensate huge

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systematic effects. Since the rotation was no more provided by the satellite, the polarimeter introduced a serious complication of the focal plane, to be added to the complication of swapping from one instrument to the other in the focal plane. Since the scientific interest of polarimetry was out of question, these mismatching were the cause of the removal of polarimeters from the major X-ray missions (Einstein, Chandra), where it was foreseen in the beginning.

Beside the advantage of being small and working at room temperature, there is the additional advantage of not requiring rotation: this removes a further area of mismatching with other instruments. The change of instruments in the focal plane is intrinsically and safely resolved by the formation flight technology itself.

The first obvious answer to the question "Why to include a polarimeter in the focal plane of XEUS?" could be that it is simple and does not require large resources.

In fact we could object that XEUS will, in any case, devote a minor fraction of its time to polarimetry. It is likely that before XEUS a dedicated mission will be flown. Such a mission could perform very long pointing of some target of particular interest and partially compensate with observing time the smaller effective area.

We will demonstrate in the following that a GPD polarimeter aboard XEUS can achieve scientific results of high value, that these results will solve some hot topics which are within the scientific targets of XEUS and that can be achieved with XEUS only, and not with a pathfinder mission of lower performance.

2. XPOL

The purpose of the XPOL is to provide, in the energy range 2 - 10keV, polarization measurements simultaneously with angular measurement (5 arcsec), spectral measurements ($E/\Delta E$ of ~ 5 @ 6 keV) and timing at few μ s level. The FOV is of 1.5×1.5 square arc minutes. XPOL is based on a Gas Pixel Detector, composed of a gas cell and a VLSI that acts as the bottom of the detector, and as Front End Electronics. The signals from the ASIC chip are delivered to an Interface Electronics, where are A/D converted and tagged with time. The whole is controlled by an electronics with a processor that analyzes the track and creates the telemetry packets. XPOL is provided with a baffle to prevent the photons from the bright X-ray sky to impinge on the detector window. A filter wheel carries calibration sources to check the stability of the detector performance with time and filters to allow for particular strategies to observe very bright sources.

2.1 The Detector

The heart of the polarimeter is the Gas Pixel Detector. It is a counter, with a beryllium window 50 μ m thick, filled with a mixture of low atomic number components (usually He 20% DME 80%). The photon is converted in an absorption/drift gap 10 mm thick. The photoelectron interacts with atoms close to the impact point and is slowed by ionization and scattered by the field of nuclei. The result is a track of electron-ion pairs. The electrons in the track are drifted by a constant electric field to a Gas Electron Multiplier, a polyimide film, metal coated on both sides, with a matrix of holes on a hexagonal pattern, with a pitch of 50 μ m. Each hole multiplies in a proportional way the charge. Therefore the track is amplified, while preserving the information on the shape and on the charge. Multiplied electrons are collected by a plane of metal pads, close to the GEM, also with hexagonal pattern and with the same pitch of 50 μ m. Each pad is the input of a complete electronic chain that detects the charge. Pads and front end electronics are part of a VLSI chip, based on 0.18 μ m CMOS technology. The chip has the capability to self trigger and fetches at the output only the content of a Region of Interest, including the pixels that triggered. Since the chip has a total of 105600 pixels, and a track typically produces a charge on 50-100 pixels (depending on the energy of the photon), this design prevents the divergence of dead-time that would be needed to read the whole detector image. The analysis of the tracks allows to derive the impact point (with a precision one order of magnitude better than that of the centroid of the charge) and the ejection direction of the primary photoelectron. The latter carries the information of the polarization of the beam. The precision on the impact point is of the order of $\sim 150 \mu$ m FWHM, largely oversampling the PSF but this is not completely exploited because of the blurring due to the absorption of photons from an inclined beam at different heights in the gas. This last effect is determining the actual resolution of XPOL.

The GPD detector and its polarimetric capabilities have been extensively described elsewhere. Below we give for XPOL figures of sensitivity which are based on experimental data on existing prototypes, without including any margin for the possible (and foreseen) improvements.^{2,4}

The level of readiness of the detector is in a good shape. Sealed prototypes, built with low desorption materials, have been tested for more than one year without any evidence of change. It should be considered that the technology for the manufacture of long duration gas cells for proportional counters and GSPCs to be employed in the space, is very well established. The stability of the mixture has been tested. Further testing for the robustness of the GEM to spark in presence of ions will be performed in a short time. Anyway it should be considered that the GEM is operated at a very low gain level (~ 500) that results in a condition much safer than that of other gas multiplication devices. A point to be clarified is the capability to handle the huge flux of data deriving from the observation of bright sources with XPOL (up to 20000 counts/second). With relatively minor changes to the ASIC chip, that will not impact on the noise figure, we think to arrive to this result. In Fig. 1 we show a prototype detector subject to vibration testing.



Figure 1. A prototype Gas Pixel detector in the facility for vibration test

2.2 The Focal Plane

According to different operative modes a filter wheel will control and determine radiation impinging on the detector. The filter wheel is a disc with different positions on it that can be rotated into the optical field of view with a motor. The Filter wheel position may be selected for observation, for calibration source deployment or for safety. Safety operations may be required autonomously or via ground control to prevent excessive charged particle flux (solar flare or local magnetospheric storms).

The filter wheel is foreseen to have 6 positions:

- Position A) Closed (Operative mode: power-off, stand-by, electrical calibration, observation*)
- Position B) Opened (Operative mode : Observation, normal rate).
- Position C) With transmission filter (Operative mode: observation, very high rate).
- Position D) With diaphragm (Operative mode : Observation, small FOV).

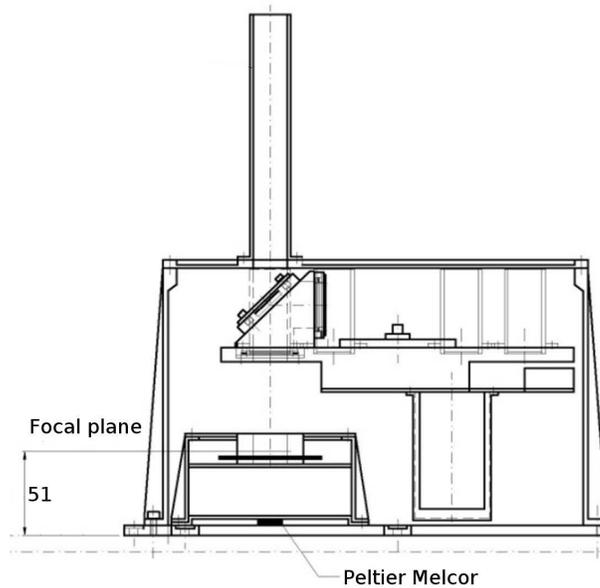


Figure 2. The focal plane of XPOL including the detector, the back-end electronics, the filter wheel and the baffle (the dimensions of the baffle are not representative)

- Position E) With calibration source I (Fe55). Operative mode : calibration.
- Position F) With calibration source Ti/Cd-109 (TBC) . Operative mode : calibration.

The presence of calibration sources aboard will be useful to monitor the stability of the gain and of the response to polarized photons. Therefore we foresee an source providing unpolarized photons and another one emitting polarized ones (by bragg diffraction). They will be put periodically in the front of the detector window.

A baffle of carbon fiber with thin metal plating will prevent the direct vision of the diffuse X-ray background from the sky. The dimension of the baffle are still to be defined, on the basis of the extension of the skirt that will surround the optics satellite.

The Detector, the back-end electronics and the filter wheel will be enclosed within a protective carter which will also support the baffle. In order to stabilize the gain the detector will have its own thermal control. In Fig. 2 we show the focal plane. The dimensions of the baffle are not representative.

2.3 The Electronics

The back-end electronics is a small box connected with the detector with flexi cables at a distance of around 20 cm. It includes the logics to program the ASIC chip, the logic to read the signal from the chip, to A/D convert them, to flag with time and to transfer to the control electronics. All the logic functions are performed by an FPGA. Near to the detector there will be also High Voltage Power Supplies.

The control electronics is a box that can be placed also at a certain distance from the focal plane consists of:

- DC/DC converters to provide stabilized low voltages
- A DSP processor
- The Mass Memory
- the housekeeping conditioner

The DPU of the control electronics programs the back-end electronics, receives the packets of events and organizes for telemetry or, alternatively, for storage in the mass memory. Since the amount of data produced by the polarimeter is high we are selecting the processor with the requirement that it is capable to perform on-board the analysis of the tracks.

Operating modes foreseen are:

- Electric calibration mode of pedestals (filter A = door closed)
- Electric calibration mode by test pulse (filter A = door closed)
- Calibration with radioactive source Fe55 (filter E)
- Calibration with radioactive source mixed (filter F)

The science modes are:

- Normal (Filter B = all open). No post-processing Diaphragm
- Diaphragm (Filter D = f.o.v partially covered). No post-processing
- High rate (Filter B = all open). Post-processing
- Extremely high rate (Filter C = all field attenuated) Post-processing

All these science operative modes are the same from the point of view of detectors and FEE configuration, time tagging, A/D conversion and zero suppression. They differ for the strategy to avoid overwhelming the mass memory in case bright sources are observed. In the normal mode data after zero suppression, the track image, are stored to the Mass Memory to be further forwarded to telemetry. In high rate, when the XPOL observation is over and the telescope is allocated to another instrument, data are recovered from the Mass Memory, compressed by DPU with onboard analysis of polarization (position, time and angle) and stored again in Mass Memory. In case the target source is faint and another stronger source is present in the field of view, the latter can be removed by the use of a diaphragm: this is the diaphragm mode. In case of an extremely bright source, that could exceed the capability of data handling, all the field will be attenuated with a filter C.

The XPOL MM is dimensioned (16 GByte) to store data from a 5000 s observation of a 1 Crab source. The same function could be performed on the P/L Mass Memory provided that it is made available for the time needed for post-processing. The processing time will normally be ≥ 20 times the acquisition time. The data flow for a very bright source could arrive to ~ 28 Mbit/s for a total memory occupation of 16GB. The processing to compress data could take ~ 5 days. After compression it would reduce to ~ 1 GByte, which could be downloaded over subsequent telemetry windows at suitably lower rate interleaved with normal science data, or special communications windows requested for this download. This means that after the pointing of a very bright source XPOL cannot be operated for around 2 days.

3. SCIENTIFIC PERFORMANCES

The science rationale of XEUS is built on three major topics:

- Co-evolution of galaxies and their supermassive black holes
- Evolution of large scale structure and nucleosynthesis
- Matter under extreme conditions

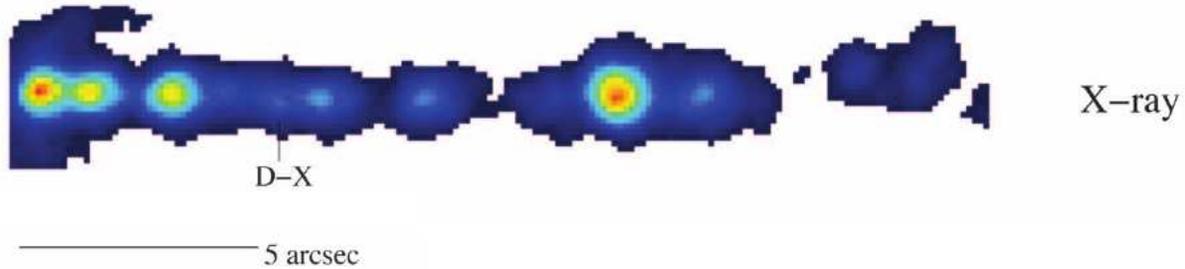


Figure 3. The X-ray image of the M87 jet by Chandra. XPOL can measure the polarization of the brightest knot down to 5%

Moreover XEUS will be open to the community to face many other scientific items as an observatory. Polarimetry will mainly contribute to the study of matter in extreme conditions. The main contribution of XEUS will be in the study of matter under extreme conditions.

One of the most interesting target for XEUS is the study of the effects of strong gravitation fields on the radiation, as predicted by General Relativity. The matter accreting on a compact object (Neutron Star or Black Hole) is organized in an accretion disk. Due to the high asymmetry of such a system the radiation emitted or scattered by the disk will have a certain degree of polarization. In 1960 Chandrasekhar⁵ had computed that the Thomson scattering in an infinitely flat cloud will produce a polarization parallel to the major axis of the projection of the disk in the sky. It will never exceed the limit of 11.7 %. Later Sunyaev and Titarchuk⁶ demonstrated that if the X-ray emission from an accretion disk is produced by the Comptonization of low frequency radiation, a very high degree of polarization can be reached for the hard radiation. Polarization can be negative (parallel to the disk axis) or positive (perpendicular to the disk axis). In any case, for reasons of symmetry the photons will be polarized perpendicular or parallel to the disk. But in the path to the observer the radiation will experience the strong gravitational field from the central object. If this is a Black Hole the effect in the observer frame will be observed as a rotation of the polarization angle. Stark Connors and Piran^{7,8} computed the effect for the case of a galactic black hole in a binary system. Since the photons of higher energy are emitted close to the BH, the rotation will be more effective at higher energies. This effect of rotation of polarization angle with energy is a unique signature of the presence of a Black Hole. Moreover the dependence of polarization amount and angle on energy will be different for Kerr and Schwarzschild black holes. This is one of the most powerful probes of gravitation near the BH horizon. The capabilities of XPOL to perform such a test on Cyg X-1 have been shown by Bellazzini et al.⁹

Another hot topics of high energy astrophysics is the structure and physics of jets. These are mainly observed by radio telescopes that provide both high resolution imaging and polarimetry. But in order to study the structure of regions of freshly accelerated electrons and improve the insight on the acceleration mechanisms themselves the X-ray imaging are a fundamental tool. Likely X-ray polarimetry will single out the formation of plasmoids by time resolved polarimetry of the central object, but XEUS, with its large collecting area and with its excellent angular resolution will give the opportunity to perform angular resolved polarimetry of knots of brighter jets. In Fig. 3 we show the X-ray structure of M87 as detected by Chandra.¹⁰ With an observation of 10^5 s XPOL can measure the polarization of knot A down to the level of 5%. It is also apparent that the angular resolution of 5 arcseconds is essential for such a measurement. Also the very faint knot of the galactic micro-quasar XTE J1550-564¹¹ can be observed by XPOL with a Minimum Detectable Polarization of 14%.

Last but not least we want to mention the capability of XPOL to test theories of Quantum Gravity. The so called Loop Quantum Gravity predicts that at very long timescale a violation of Lorentz invariance occurs. The two states of circular polarization have a different velocity and this difference increases with energy. Since also the wave-number is proportional to the energy of the radiation, the total effect is a rotation of the polarization plane with the distance and with the square of the energy.¹² The amount of this effect of birefringence is unknown

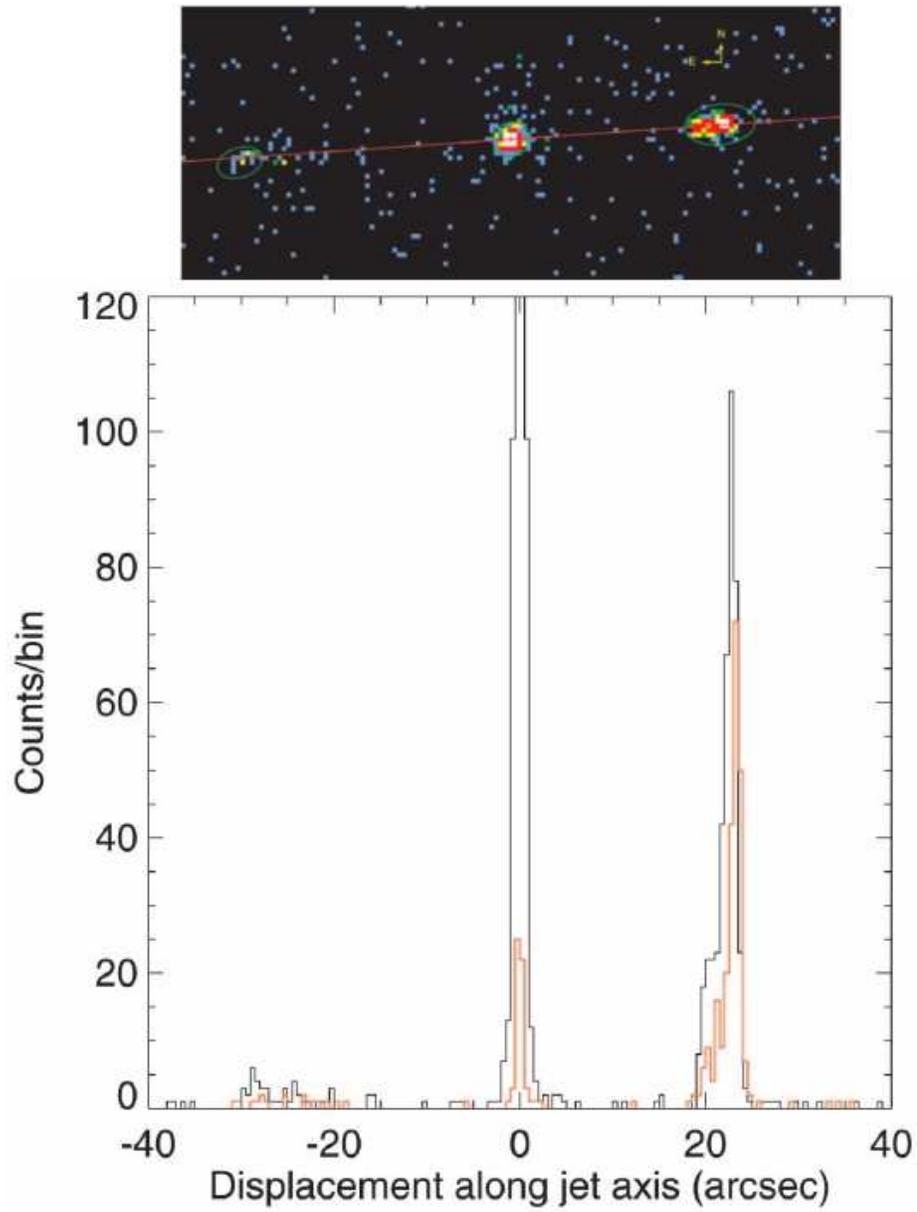


Figure 4. The very faint jet of the micro-quasar J1550-564. The Minimum Detectable Polarization for one day observation with XPOL is 14%

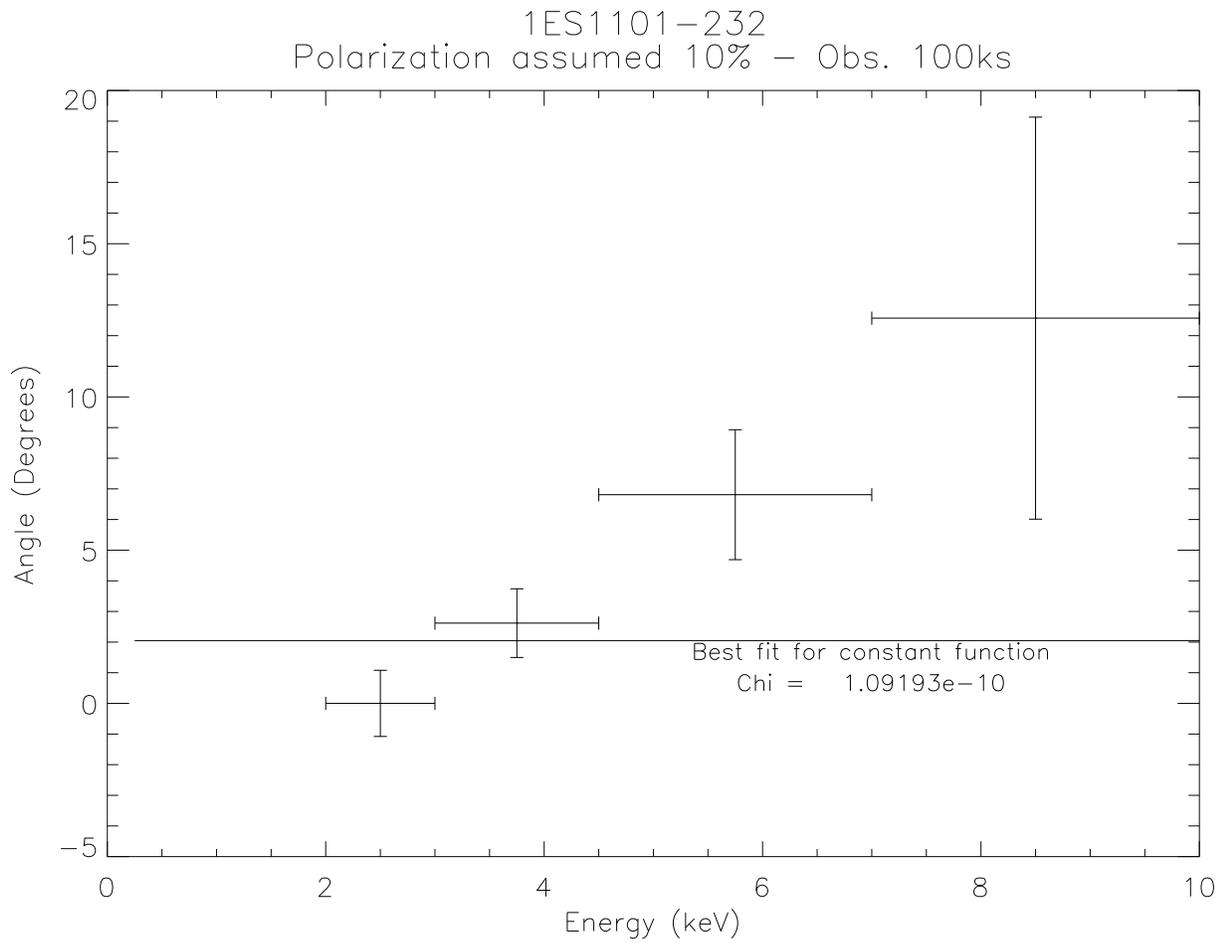


Figure 5. The minimum variation of the polarization angle of blazar 1ES1101-232 ($z=0.186$) detectable by XPOL in one day at 3σ level.

and only upper limits are there. But since this is one of the few ways to derive experimental information about QG theories, the continuous search for more sensitive measurements (even of upper limits) is a worthwhile task. X-ray is the highest energy band where sensitive polarimetry of sources at cosmologic distances can be performed. We assume that Blazars are good candidates to have a high degree of polarization with angle independent on the energy (at least within a decade). If this hypothesis is verified on nearby blazars (in the synchrotron regime) we move to far-away blazars and search for a rotation of polarization angle with the energy proportional to the distance. In Fig. 5 we show that XPOL is capable to reject at 3σ the hypothesis of constant angle with a 100ks observation of blazar 1ES1101-232 if the coupling constant is 1×10^{-10} . This would improve of 5 orders of magnitude the previous upper limit.

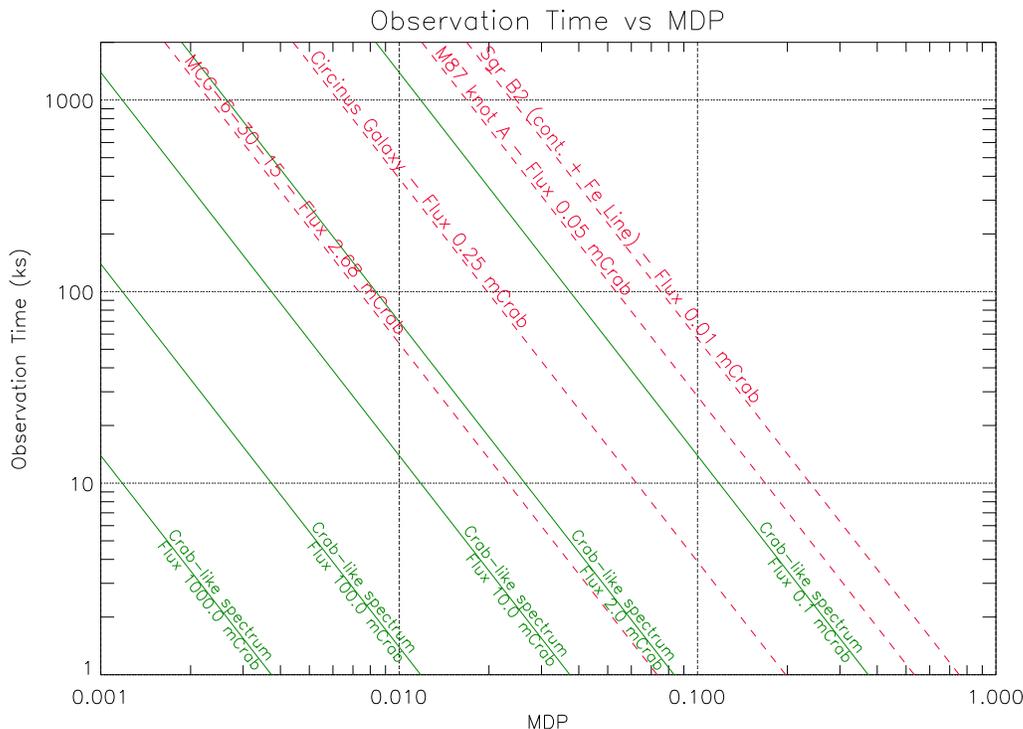


Figure 6. The Minimum Detectable Polarization as a function of observing time for a few representative sources

4. CONCLUSIONS

XPOL aboard XEUS is capable to perform some measurements which are a significant step forward in High Energy Astrophysics and that cannot be performed by none of the various lower profile proposed missions. In Fig. 6 we show the time needed to achieve a certain level of Minimum Detectable Polarization with XPOL.

XEUS is unique mainly under two respects:

- The collecting area two orders of magnitude larger than any dedicated mission
- The angular resolution of few arcseconds that derives from the long focal length. With such a length also the blurring due to the finite thickness of the detector is not very effective.

How would it compare with pathfinder missions? XEUS could reasonably dedicate to polarimetry only a fraction of its time (let us say 1/10) while a pathfinder could perform full time polarimetry. The step in surface to have a drastic improvement with respect to pathfinders is of two orders of magnitude.(namely the area should be of $\approx 5m^2$). Both these parameters are subject to a potential reduction in the frame of design trade-off in order

to decrease costs or weights or, simply, to cope the performance of the actual optics technology. A decrease of collecting surface R_s results in a proportional increase of the observing time: $t \rightarrow t/R_s$. Or In a reduction of MDP as $R_s^{1/2}$ for the same observing time e.g. this would result in:

- a reduced sample of AGN, with a poorer coverage of parameter space
- a significant loss of sensitivity to variability of polarization angle with time (namely on testing strong gravity in extragalactic BHs).

On the other side, since the source will still exceed the background a relaxation of the angular resolution would not impact on polarimetric sensitivity. but Would miss a few topical targets that only XEUS can do. The most important: polarimetry of all details of the Crab and of other Pulsar Wind Nebulae, polarimetry of jets (galactic and extragalactic), polarimetry of bright knots of shell-like SNR, fast variability of polarization angle, due to General Relativity effects, in AGN.

Acknowledgments

The authors acknowledges financial support from Agenzia Spaziale Italiana (ASI).

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