The PoGOLite balloon-borne soft gamma-ray polarimeter

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Abstract. Linearly polarized radiation in the hard X-ray/soft gamma-ray band is expected from a large variety of astronomical sources. We discuss the importance of polarimetric studies for several classes of sources – pulsars, accreting black holes, magnetic neutron stars and jets from active galaxies – and then describe PoGOLite, a balloon-borne instrument which is currently under construction and will be able to measure the polarization of electromagnetic radiation from such extra-solar objects in the energy range 25–80 keV.

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INTRODUCTION

Linear polarization in the hard X-ray/soft gamma-ray band can be produced by Compton reflection and by emission and radiation transfer in strong magnetic fields. Polarized radiation in this band is expected from many types of sources, including black hole systems and neutron stars. As shown by observations at longer wavelengths, polarization is a powerful diagnostic tool, providing information about source structure, geometry and radiation processes. To date, despite the importance of such measurements, only one statistically significant measurement of an extra-solar source has been published and gained wide acceptance: an observation of the Crab nebula at 2.6 keV and 5.2 keV which was done in the 1970s with an instrument on-board the OSO–8 satellite [1]. Here, we describe PoGOLite, a new polarimeter scheduled for its first flight in August 2010.

POLARIMETRIC STUDIES

Pulsars and pulsar wind nebulae

The Crab nebula and its pulsar are obvious targets for high-energy polarimetry. For rotation-driven pulsars, it is not yet clear if the high-energy radiation originates close to the magnetic poles (polar cap model), near the light cylinder (outer gap model) or in the intermediate region (caustic model). The available models predict drastically different polarization properties. In particular, the predictions for the modulation of the polarization angle over the spin period exhibit significant differences and polarimetry can therefore be used to distinguish between emission models, e.g. for the Crab pulsar [2].

Accreting black holes

Many black hole binaries exhibit transitions between two spectral states, a hard and a soft state [3], and changes between the states are expected to be evident in the polarization signature of such sources. Spectral models imply that a reflection component is often present in the hard-state X-ray flux from X-ray binaries. This component is expected to be polarized with a strength and orientation depending on the inclination of the system and orientation of the accretion disc [4, 5]. In favorable cases, the net polarization may reach (or even exceed) 10%. A measurement of the strength and energy dependence of the polarization would provide a direct test of the reflection models. Such observations would also allow a test of models suggesting that part of the high-energy emission is due to synchrotron processes in a collimated outflow or jet [6], in which case a much stronger polarization is predicted. In the soft state, the hard X-ray emission is believed to be produced by Compton scattering of photons on non-thermal electrons in active regions above the disc. The polarization properties are more difficult to predict in this case since there is a larger range of possibilities for intrinsic polarization, reflection and variability. Polarimetry could here provide new clues to the origin of the high-energy tail in this state. A prime target for such a measurement is Cygnus X–1.

For radiation passing close to the black hole, general relativistic effects will produce an energy-dependent rotation of the polarization plane [7]. Since the predicted effect depends strongly on the rotation of the black hole, polarization measurements can potentially be used to deduce the black hole spin.

Accreting magnetic neutron stars

In strong magnetic fields (of order 10^{12} gauss) near accretion-driven X-ray pulsars, the emitted radiation is expected to be polarized. As the neutron star rotates, the orientation of the magnetic field with respect to our line of sight will change and so will the orientation and strength of the polarization. One of the main problems in the accretion models of these sources is how the accreting matter is decelerated as it hits the neutron star. Deceleration by Coulomb collisions would give a thin hot plasma slab, while a stand-off shock would result in a vertically extended hot radiating column [8]. The two geometries will have opposite correlations between flux and polarization, and polarimetry can therefore be used to distinguish between the two cases. An excellent candidate for such a measurement is Hercules X–1.

Jets from active galaxies

Many active galaxies are associated with relativistic jets and are seen as blazars when the jets are pointing towards us. Currently, the formation, acceleration, collimation and contents of these jet are not well-understood. The observed overall spectral distribution has two broad humps and in most models, these are explained as synchrotron and inverse Compton components, respectively (see e.g. [2] and references therein). X-rays and soft gamma-rays correspond to energies that typically fall in the region between these peaks and polarimetry in this energy range would be a valuable diagnostic of different jet models. A prominent source for this kind of measurement is Markarian 501.

THE POGOLITE POLARIMETER

We are currently constructing the Polarized Gamma-ray Observer, PoGOLite [2], a balloon-borne instrument which is optimized for point-sources and will measure polarization from the sources described above in the energy range 25–80 keV. Extending the energy range as low as to 25 keV is a crucial feature of the instrument due to the rapid decrease in photon flux with increasing energy. By using a combination of both active and passive shielding, as well as active and passive collimation, the instrument will be able to measure as low as 10% polarization from a 200 mCrab source in a single six-hour flight. The expected performance of the instrument is detailed in Table 1.

TABLE 1. Expected PoGOLite performance at an atmospheric overburden of 4 g/cm^2 [2].

	25 keV	40 keV	50 keV	80 keV
Min. detectable pol. in 6 h, 100 mCrab source		10.5%		
Min. detectable pol. in 6 h, 200 mCrab source		6.5%		
Eff. area for polarimetry (air attenuation not incl.)	93 cm^2	228 cm^2	198 cm^2	158 cm^2
Modulation for 100% pol. beam with Crab spectrum	33%	26%	27%	40%
Field of view:	1.25 msr (2.0° × 2.0°)			
Geometric area:	994 cm^2			
Time resolution:	1 μs			

Instrumental design

The instrument is based on the Compton technique [9, 10]. Since photons have a higher probability to scatter perpendicularly to the polarization vector, the distribution of azimuthal scattering angles will be modulated for photons from a polarized beam. In PoGOLite, scattering angles are measured by individually tracking photons through coincident detection of Compton scattering and photoelectric absorption in a segmented detector volume comprising 217 well-type phoswich detector cells (PDCs) in a hexagonal array surrounded by a segmented side anticoincidence shield (SAS) made of BGO crystals (Fig. 1). A polyethylene shield, 10 cm on the sides of the instrument and 15 cm in the bottom, is used to minimize the neutron-induced background, and the instrument will rotate around the viewing axis in order to remove systematic bias.

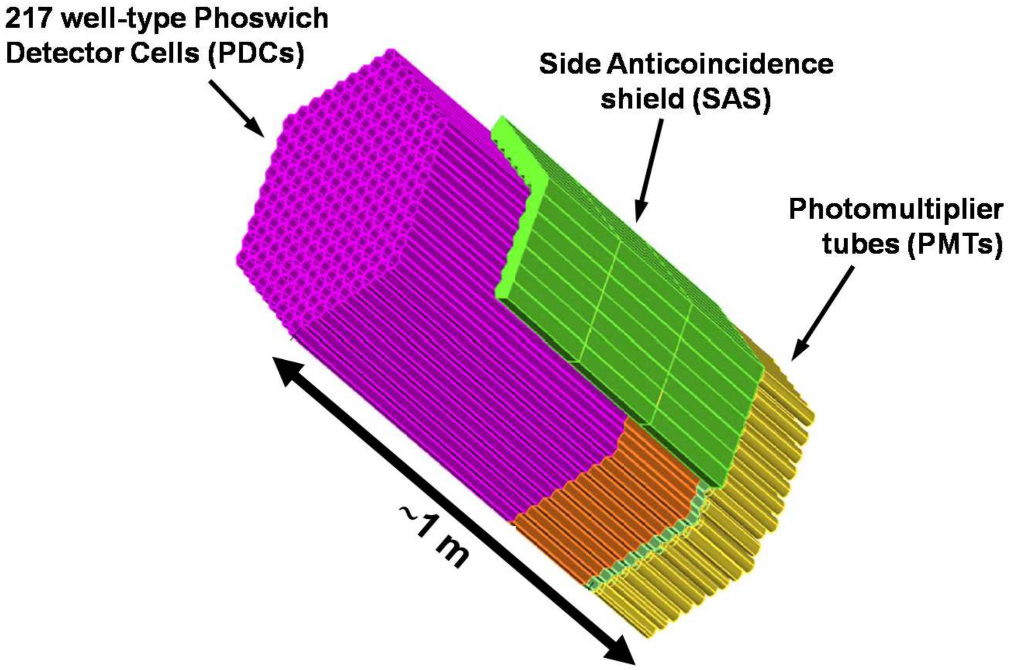

FIGURE 1. Sketch of the PoGOLite instrument, consisting of 217 phoswich detector cells surrounded by a side anticoincidence shield. For clarity, the polyethylene neutron shield is not included in this sketch, and only part of the anticoincidence shield is shown.

Each PDC [2] comprises three components: a hollow "slow" plastic scintillator (60 cm long), a solid "fast" plastic scintillator (20 cm) and a bottom BGO crystal (4 cm). The slow scintillator tube acts as an active collimator, limiting the field of view to about 1.25 msr ($2.0^\circ \times 2.0^\circ$). Photons and charged particles entering the instrument from the rear are detected in the bottom BGO crystals. The fast scintillator is the detector component where Compton scatterings and photoelectric absorptions take place. The three components are viewed by a single photomultiplier tube, and by using pulse shape discrimination based on the scintillation decay times of the materials, signals from the different components can be distinguished [11].

Events of interest are photons that go through the slow scintillator tube without interacting, scatter in the fast scintillator of one cell and undergo absorption in the fast scintillator of a separate cell. The relative energy deposition in the involved detector cells can be used to reconstruct the path of the photons and the angular distribution of the scattered photons gives the polarization [12]. The concept is shown in Fig. 2.

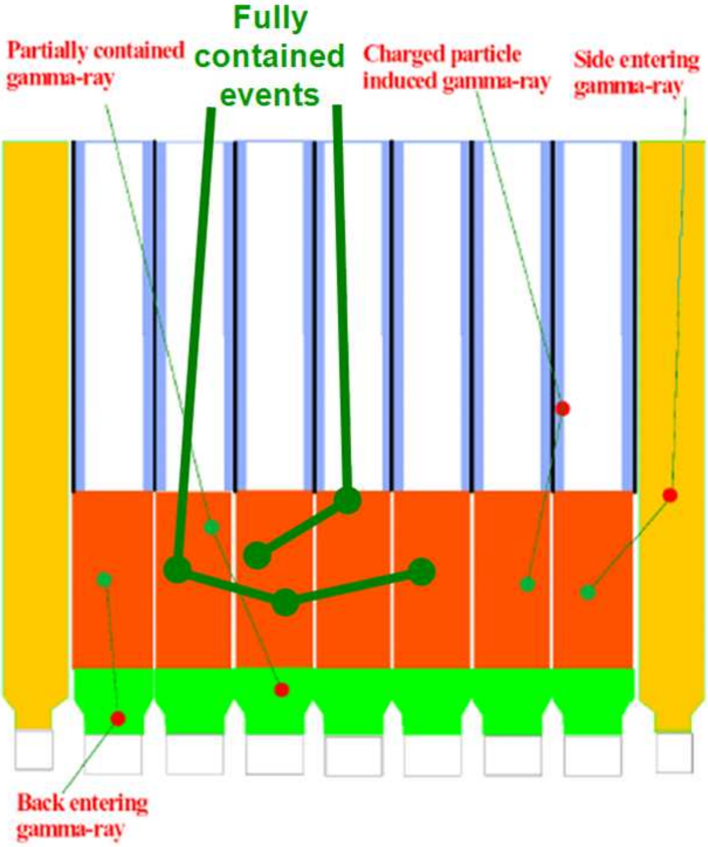

FIGURE 2. Simplified sketch of the PoGOLite detector array (not to scale, not all detector cells shown) with different kinds of interactions. Events from photons interacting in the side anticoincidence shield, collimator tubes or bottom BGO crystals are rejected.

Our simulations show that polarization can reliably be reconstructed by including events from photons interacting in up to three different detector cells [13]. For a simulated Crab spectrum, less that 20% of the events in the PoGOLite energy range are from photons interacting in more than three cells [14].

Studies of in-flight background

Background is often a challenge in ballooning missions, and in order to confirm that the PoGOLite instrument can meet the specified observation goals, the background has been carefully studied in simulations within the Geant4 framework [15]. These simulations [16] include cosmic and atmospheric gamma-ray background, structure-induced background i.e. signals from secondary radiation produced by cosmic rays interacting in dead materials surrounding the instrument, and background from atmospheric neutrons. The expected background spectrum in the PoGOLite energy range is presented in Fig. 3.

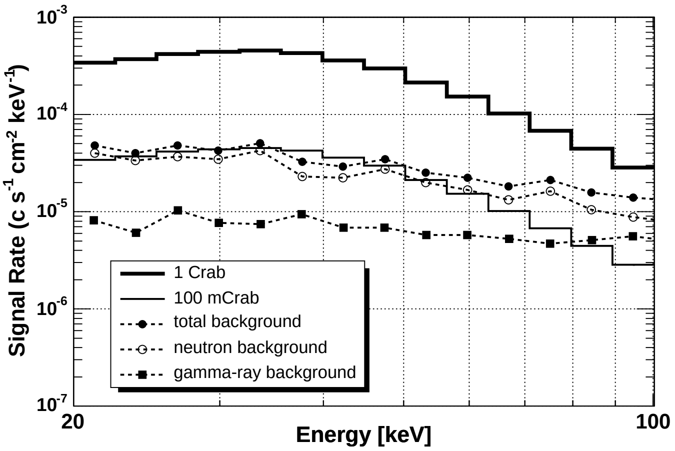

FIGURE 3. Expected in-flight background of the PoGOLite instrument at an atmospheric overburden of 4 g/cm^2 [2]. A 1 Crab source and a 100 mCrab source are shown for comparison.

Structure-induced background has been found to be negligible both in Geant4 simulations [16] and in calculations [2] based on empirical formulas, but as shown in Fig. 3, the background from atmospheric neutrons is significant, exceeding the gamma-ray background by almost an order of magnitude. Our simulations show, however, that this level is still manageable, thanks to the polyethylene neutron shield [16].

Performance validation

In order to validate our simulations of the neutron-induced in-flight background, laboratory tests [12] were carried out with 14 MeV neutrons irradiating a small detector array consisting of four plastic scintillators and three BGO anticoincidence crystals surrounded by a polyethylene neutron shield. We measured the neutron count rate in the central detector unit with different thicknesses of the polyethylene shield and under different event rejection criteria. In the measurement, the neutron count rate in the central detector cell decreased by $(42 \pm 4)\%$ when the active anticoincidence system was active, while the corresponding value from our simulation was $(43 \pm 1)\%$. The neutron spectrum is also well-reproduced in the simulation. Similar agreement was found for all combinations of polyethylene shield thicknesses and neutron event rejection criteria [12]. The excellent agreement demonstrates that our simulation environment for treating neutron interactions in Geant4 is reliable. Since the largest contribution to background in the PoGOLite energy range is from neutrons of a few tens of MeV, similar to the 14 MeV neutrons used in this test, this agreement confirms our claim that the background from atmospheric neutrons can be reduced to a manageable level.

Several beam tests have been carried out with a polarized beam of synchrotron photons irradiating a prototype of the PoGOLite instrument (see [12] for a review). Results from the measurements have been in line with expectations based on Geant4 simulations, thus demonstrating the performance of the instrument.

PoGOLite Pathfinder

A 61-unit proof-of-principle instrument, the PoGOLite “Pathfinder” (Fig. 4), is currently under construction in Stockholm. It is scheduled for its first flight from the Esrange ballooning facility in Northern Sweden in August 2010. The instrument will be used to measure polarization from the Crab nebula and Cygnus X–1, as well as to assess in-flight background in preparation for the flight of the full-size instrument.

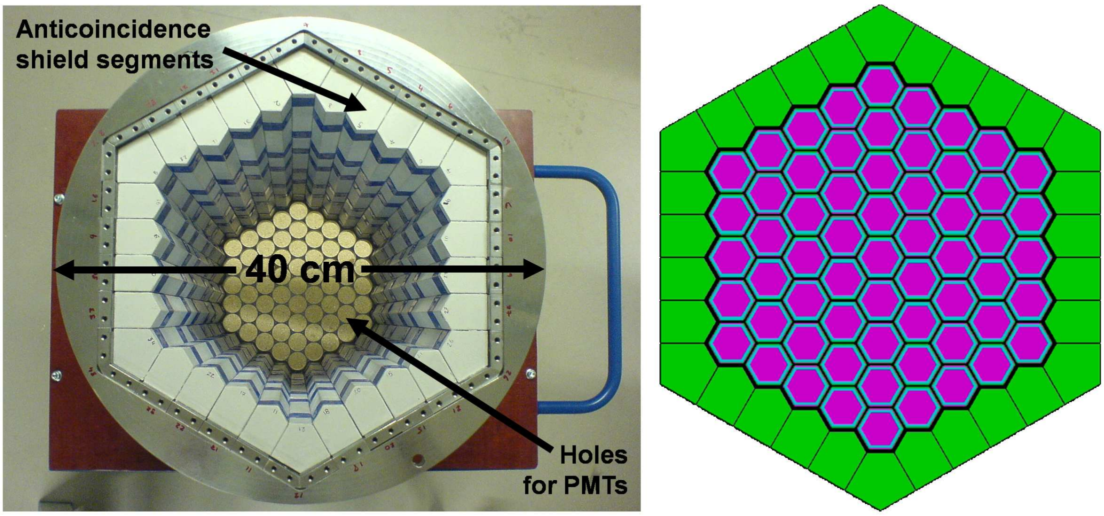

FIGURE 4. Top view of the detector array mechanics of the PoGOLite Pathfinder currently under construction in Stockholm (left) and a sketch of the 61-PDC detector array (right).

The spin axis of the Crab system has been predicted to be at about 124°–126° based on observations with the Chandra X-Ray Observatory [17]. X-ray emission from the Crab is believed to be synchrotron emission from high-energy electrons trapped in toroidal magnetic structures around the system [18], and if this model is correct, the polarization angle of the X-ray emission is expected to be parallel with the spin axis of the system [2]. However, using an instrument on-board the OSO–8 satellite, the polarization angle at 2.6 keV and 5.2 keV was measured [1], and was found to be rotated relative to the spin axis by about 30°. If a 19% polarization degree, as measured on-board OSO–8, is assumed in the PoGOLite energy range, the Pathfinder instrument will be able to measure the polarization degree of the Crab nebula with a 7σ significance and determine the polarization angle with a precision of about 5° in a single six-hour flight. Such a measurement will not only reveal whether the polarization degree remains constant with energy, but also determine if the polarization angle aligns with the spin axis at higher energies, thus testing the paradigm that the X-ray emission from the system is synchrotron emission from electrons trapped in magnetic torii around the pulsar [2].

For Cygnus X–1 in the hard state, the PoGOLite Pathfinder will be able to measure as low as 10% polarization. This enables the predicted energy dependence of the polarization to be tested against measurements [9].

SUMMARY AND OUTLOOK

PoGOLite is a balloon-borne polarimeter designed to measure polarization from extra-solar sources in the energy range 25–80 keV. Using well-type phoswich detector technology in combination with active and passive shielding, the instrument is able to measure a 10% polarization from a 200 mCrab source in a six-hour flight, despite the severe atmospheric background associated with measurements on-board high-altitude balloons.

A scaled-down version of the PoGOLite instrument, comprising 61 phoswich detector cells instead of 217, is currently under construction in Stockholm and is scheduled for its first flight in August 2010. This instrument, the PoGOLite Pathfinder, will be able to measure the polarization degree of the Crab nebula with a 7σ significance, testing the paradigm that the X-ray emission from the Crab system is synchrotron emission from electrons trapped in magnetic torii around the Crab pulsar, and also as low as 10% polarization from Cygnus X–1, allowing the energy-dependence of the polarization to be tested.

After the completion of the PoGOLite Pathfinder, focus will be shifted to the full-size instrument. Different types of flights are foreseen: short flights (6–8 hours) are suitable for studying one source, e.g. Cygnus X–1 or the Crab system. Long-duration flights (about one week) from Sweden to Western Canada are also possible, during which one can observe multiple sources or study temporal variations of one single source. The possibility of full circumnavigations is also being investigated and would greatly increase the time on source for several of the sources of interest.

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