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PoGOLite: a balloon-borne soft gamma-ray polarimeter

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Abstract: Polarized gamma-rays are expected from a wide variety of sources including rotation-powered pulsars, accreting black holes and neutron stars, and jet-dominated active galaxies. Polarization measurements provide a powerful probe of the gamma-ray emission mechanism and the distribution of magnetic and radiation fields around the source. No measurements have been performed in the soft gamma-ray band where non-thermal processes are expected to produce high degrees of polarization. The PoGOLite experiment applies well-type phoswich detector technology to polarization measurements in the 25 - 80 keV energy range. The instrument uses Compton scattering and photoabsorption in an array of 217 phoswich detector cells made of plastic and BGO scintillators, and surrounded by active BGO shields. A prototype of the flight instrument has been tested with polarized gamma-rays and background generated with radioactive sources. The test results and computer simulations confirm that the instrument can detect 10% polarization of a 200 mCrab source in one 6 hour balloon observation. In flight, targets are constrained to within better than 5% of the field-of-view (~5 degrees squared) in order to maximize the effective detection area during observations. The pointing direction on the sky is determined by an attitude control system comprising star trackers, differential GPS receiver system, gyroscopes, accelerometers and magnetometers which provide correction signals to a reaction wheel and torque motor system. Additionally, the entire polarimeter assembly rotates around its viewing axis to minimize systematic bias during observations. Flights are foreseen to start in 2009-2010 and will target northern sky sources including the Crab pulsar/nebula, Cygnus X-1, and Hercules X-1. These observations will provide valuable information about the pulsar emission mechanism, the geometry around the black hole, and photon transportation in the strongly magnetized neutron star surface, respectively. Future goals include a long duration balloon flight from the Esrange facility in Northern Sweden to Canada.

Scientific goals

The underlying processes postulated to explain the emission mechanisms of compact astrophysical sources (such as accreting black holes, astrophysical jets, and pulsating neutron stars) result in polarized fluxes of soft gamma rays. The polarization arises naturally for synchrotron radiation in ordered magnetic fields and for photons propagating through a strong magnetic field. Polarization can also result from Compton scattering in the material surrounding a source. In all cases, the orientation of the polarization plane is a powerful probe of the geometry of sources. The balloon-borne PoGOLite experiment aims to provide the first polarimetric measurements in the soft gamma-ray regime for many classes of astrophysical sources. Despite the wealth of sources accessible to polarization measurements and the importance of these measurements, polarization at high energies has been measured only at 2.6 keV and 5.2 keV for the Crab nebula by an experiment on the OSO-8 satellite in 1976 [1]. Polarization has never been measured at soft gamma-ray energies where non-thermal processes are likely to produce high degrees of polarization. Since this is a largely unexplored field, potential targets are numerous. Initial targets of PoGOLite will be a rapidly-rotating neutron star, the Crab (with the pulsar and nebula components separated) and an accreting black hole, Cygnus X-1. The feasibility of measuring energy dependent polarization has been studied [2]. Other potential targets include accreting magnetic neutron stars (e.g. Hercules X-1), jets in active galaxies (e.g. Mkn 501) and galactic binaries, as well as searches for Planck Scale Lorentz symmetry violation (using Mkn 501, Crab nebula).

Emission mechanisms in isolated pulsars

The Crab pulsar will be PoGOLite's first target. In so-called 'rotation-powered pulsars', like the Crab, the emission region is known to be different in different wavelength bands. Historically, phase-resolved polarimetry has had enormous diagnostic capability at radio and optical wavelengths. The expected signature of emission near the poles of a dipole field, an 'S'-shaped swing of the polarization position angle through the pulse profile [3], has been seen from many radio pulsars and is generally accepted as proof that the radio emission originates from the open field lines of a magnetic dipole. In the X-ray and gamma-ray regimes, each pulse period reveals two peaks, so-called P1 and P2 (see figure 1). A phase-resolved polarization measurement of the corresponding soft gamma-ray flux will indicate where in the magnetosphere the emission occurs. In the caustic model [4], the Crab pulse profile is a combination of emission from both poles, whereas in both the polar cap [5] and outer gap [6] models, radiation is seen from only one pole or region. Figure 1 shows theoretical polarization position angle and polarization degree as a function of pulse phase for the outer gap, polar cap and slot gap or 'caustic' models. The PoGOLite instrument will distinguish between these three models using P1 alone. Predictions of polarization at P2 for the 3 models are rather similar. Measurements of the region between the two peaks will also be important in understanding the pulsar emission mechanism in the gamma-ray band. Even if none of these models turns out to be correct, the data from one flight will provide extraordinary constraints upon any future models.

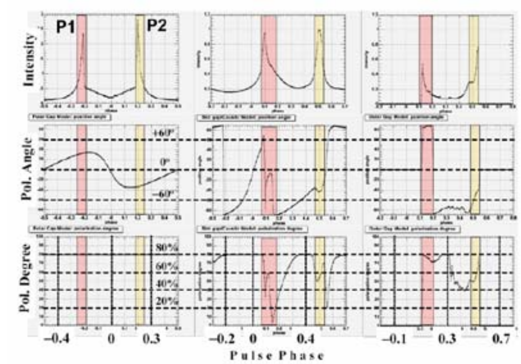

Figure 1: Models of pulse profile (top), polarization position angle (middle) and polarization degree (bottom) for the Crab pulsar used in PoGOLite simulations. The polar cap (left) and caustic (center) models are from Dyks [4], while the outer gap model (right) is from Romani [6]. The polarization degree inferred from optical measurements [7] is assumed for the outer gap model. P1 is 3.3ms wide and P2 is 6.6ms wide. The numerical data is provided by Alice Harding.

Instrument design

The PoGOLite experiment applies well-type phoswich detector technology to polarization measurements in the 25 - 80 keV energy range [8]. The instrument uses Compton scattering and photo-absorption in an array of 217 phoswich detector cells (PDC) made of plastic and BGO scintillators, surrounded by active BGO shields, as shown in figure 2. Each PDC is composed of a thin-walled tube (well) of slow plastic scintillator at the top (fluorescence decay time ~285 nsec), a solid rod of fast plastic scintillator (decay time ~2 nsec), and a short bismuth germanate oxide (BGO) crystal at the bottom (decay time ~300 ns), all viewed by one photomultiplier tube (PMT). The wells serve as a charged particle anticoincidence, the fast scintillator rods as active photon detectors, and the bottom BGOs act as a lower anticoincidence. Each well is sheathed in thin layers of tin and lead foils to provide passive collimation. The instrumental assembly is surrounded by a 10 cm think layer of paraffin to reduce background from atmospheric neutrons. Figure 2 shows a simplified cross-section of the instrument with possible gamma-ray interactions indicated.

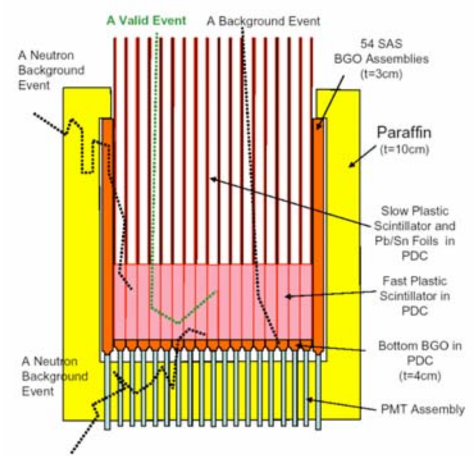

Figure 2: Schematic cross section of the PoGOLite instrument (not to scale) showing valid and background photon interactions. Possible background atmospheric neutron interactions are also shown.

Gamma-rays entering within the field of view of the instrument, 1.2 msr (~2.4 degrees)^2, defined by the slow plastic collimators) will hit one of the fast plastic scintillators and may be Compton scattered, with a probability that depends on the photon energy. The scattered photon may escape, be photoabsorbed in another detector, or undergo a second scattering. Electrons resulting from Compton scattering or photoabsorption will deposit their energy in the plastic scintillator and produce a signal at the PMT. A trigger based on the photoelectron energy deposit will initiate waveform recording of PMT outputs from all PDCs. Valid Compton scattering events will be selected from these waveforms after the completion of a flight. The locations of the PDCs in which the Compton scatter and photo-absorption are detected determine the azimuthal Compton scattering angle. The geometry of the PDC arrangement limits the polar scattering angle to approximately (90±30) degrees, roughly orthogonal to the incident direction. Little of the energy of an incident gamma-ray photon is lost at the Compton scattering site(s), and most of the energy is deposited at the photo-absorption site. This makes it straight-forward to differentiate Compton scattering sites from photo-absorption sites. The azimuthal Compton scattering angles will be modulated by the polarization of the photon. The polarization plane can be derived from the azimuthal distribution of scattering angles. The degree of polarization (%) is determined by the ratio of the measured counting rate modulation around the azimuth to that predicted for a 100% polarized beam (from simulations calibrated with experiments at polarized photon beams).

Performance studies

The expected azimuthal modulation for P1 for the Crab (as defined in Figure 1) has been simulated for a 6 hour long observation at the top of the atmosphere (~40 km, ~4 g/cm^2) and is shown in Figure 3. In this calculation, the nebula component is assumed to be polarized with the degree and angle as measured by OSO-8 [1]. Figure 4 shows the expected background levels to this measurement derived from simulations. A 7-unit PoGOLite prototype (6 peripheral units arranged symmetrically around a central unit) partly equipped with an anticoincidence shield was tested at the KEK photon factory in Japan in March 2007. Data were taken at several beam energies between 25 keV and 80 keV. The beam polarization was (87.8±0.4)%.

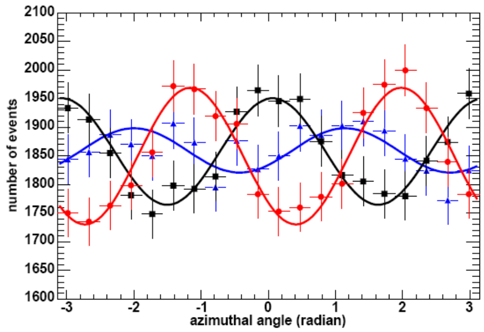

Figure 3: The polarization signal that PoGOLite will measure in 6 hrs at the top of the atmosphere for P1 of Crab Pulsar (defined in Figure 1) for the polar cap (red), slot gap/caustic (blue) and outer gap (black) models.

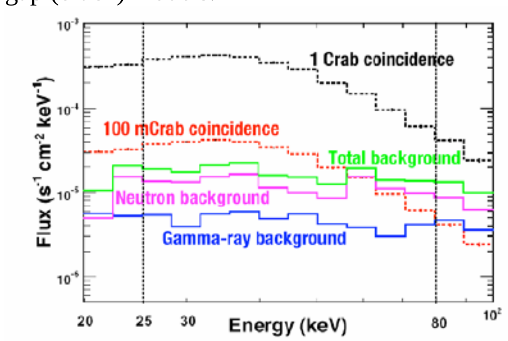

Figure 4: Valid and background event rates for PoGOLite: valid event rates expected from a 1000 mCrab source (black dotted line) and a 100 mCrab source (red dotted line) at a conservative 4 g/cm^2 atmospheric overburden. The total (green solid line), neutron [9] (purple solid line) and gamma-ray [10] (blue solid line) backgrounds are shown. Neutrons and gamma-rays produced in the PoGOLite gondola structure by cosmic-ray particles have been calculated to be negligible.

The data were taken using the waveform sampling electronics system foreseen for flight. Signals from the PMT last dynodes were fed to individual preamplifiers and discriminators. All signals were continuously digitized at 20MHz. Detection of a waveform compatible with being a clean hit on a fast scintillator with energy deposition greater than ~10keV triggered the data acquisition. Events with a photo-absorption waveform in a peripheral unit and a Compton scattering waveform in the center unit (where the beam was directed) were selected from the data. Figure 5 shows the fast-slow 2-dimensional distribution for recorded waveforms. Candidate Compton scattering and photo-absorption events can be readily identified between the red lines. Such events have been used to determine the polarization of the incident photon beam.

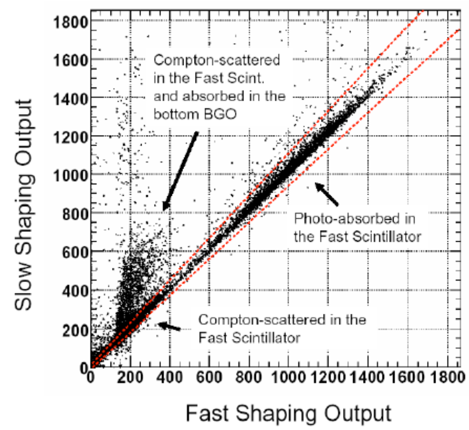

Figure 5: Results from the 50 keV run of the 2007 KEK beam test shwing the correlation between events classified as ‘fast’ (horizontal axis) and ‘slow’ (vertical axis) by waveform sampling. Events between the two red lines correspond to clean hits in a fast scintillator and can be used to determine the beam polarisation.

References

[1] M.C. Weisskopf et al., ApJ 208 L175 (1976).
[2] M. Axelsson et al., astro-ph/07041603.
[3] V. Radhakrishnan et al., Astrophys Lett 3 225 (1969).
[4] J. Dyks, ApJ 598 1201 (2003). J. Dyks, ApJ 606 1125 (2004).
[5] S. Sturner et al., ApJ 445 736 (1995). J. Daugherty et al., ApJ 458 278 (1996).
[6] K.S. Cheng et al., ApJ 300 500 (1986). R. Romani, ApJ 438 314 (1995). R. Romani, ApJ 470 469 (1996).
[7] F. Smith et al., MNRAS 233 305 (1988).
[8] Y. Kanai et al., Nucl. Instr. and Meth. A 570 (2007) 61.
[9] J. Kazejev, Master’s Thesis, KTH Stockholm, June 2007. T.W. Armstrong et al., J. Geophys. Res. 78, (1973) 2715. T.W. Armstrong et al., 1997, Conference on High Energy Radiation.
[10] T. Mizuno et al., ApJ, 614 (2004) 1113.