MEASURING POLARIZATION WITH SPI ON INTEGRAL

E. Kalemci[1], S. Boggs[1], C. Wunderer[1], and P. Jean[2]
[1]Space Sciences Laboratory, UC Berkeley, 7 Gauss Way, Berkeley, CA, 94720-7450, USA,
emrahk@ssl.berkeley.edu
[2]Centre d'Etude Spatiale des Rayonnements, CNRS/UPS, BP 4346, 31028 Toulouse, France,
Pierre.Jean@cesr.fr

ABSTRACT

We have investigated the feasibility of detecting polarization using the coincidence (multiple) events in SPI (Vedrenne et al. 2003). We conducted Monte-Carlo simulations to determine the modulation factor as a function of energy. Using the modulation factors and the observed and expected source and background count rates from several astrophysical sources we have determined the minimum detectable polarization levels. We found that a moderately bright gamma ray burst in the field of view of SPI offers the best chance for detecting polarization and determining polarization fraction and angle.

Key words: INTEGRAL; SPI; Gamma-rays; Polarization.

1. INTRODUCTION

Gamma-ray astronomy primarily uses imaging, spectral, and temporal analysis techniques to study astrophysical phenomena. Even with this variety, differing theories often explain the same phenomena. Polarization is a strong tool for breaking the degeneracy of many models. For example, the measurement of strong polarization in the prompt emission of GRB021206 (Coburn & Boggs 2003) has already prompted numerous papers on the origin of GRBs (Lyutikov et al. 2003; Granot 2003; Lazzati et al. 2004, and references therein). The radio and the optical community have been taking advantage of using polarization, especially to study outflows, which are ubiquitous in black hole binaries and AGNs. These sources are also strong X-ray and gamma-ray emitters. Detection of strong gamma-ray polarization from a black hole binary with the polarization angle consistent with the radio measurements would be a strong indication for the synchrotron origin from a compact jet for the high energy emission, and would revolutionize the approach to explain all aspects of X-ray and gamma-ray emission from a black hole binary system. The list of potential applications of gamma-ray polarization can be made longer (see, for example, proceedings of the X-Ray Polarimetry Workshop held at SLAC, Stanford, California, 9-11 February 2004, http://heasarc.gsfc.nasa.gov/docs/heasarc/polar/polar.html)

Polarized gamma-rays tend to scatter at right angles to the incident polarization vector, resulting in an azimuthal scatter angle distribution that is modulated relative to the distribution for non-polarized photons. Both the IBIS and SPI instruments on the INTEGRAL observatory can measure such modulation, and therefore measure polarization: IBIS through its Compton mode (coincident events in ISGRI and PICsIT) and SPI through multiple detector events (ME). In this poster, we concentrate on the polarization capabilities of SPI. We have simulated the azimuthal scatter angle distribution of polarized and non-polarized photons, as well as studied the background distributions in SPI, to calculate the minimum detectable polarization levels for GRBs, and the Crab nebula.

2. BASIC PRINCIPLES OF POLARIZATION

For photons with energies higher than a few hundred keV, Compton scattering is the main mechanism of interaction with the SPI detectors. This enables SPI to measure polarization since linearly polarized γ-rays tend to scatter perpendicular to the incident polarization vector (see Fig. 1 for the illustration of scattering vectors and angles). For example, if the polarization angle η is in the $\hat{x}$ direction in Fig. 1, the polarized photons would preferentially scatter in the $\pm\,\hat{y}$ direction.

The sensitivity of a detector to polarization is determined by its effective area to the scatter events, and the average value of the polarimetric modulation factor Q, the maximum variation in azimuthal scattering probability for 100% polarized photons (Lei et al. 1997).

The tendency of azimuthal scattering perpendicular

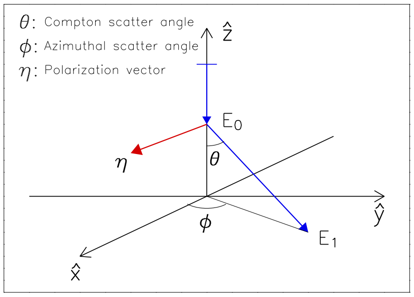

Figure 1. This figure shows the basic angles and vectors that are used in defining polarization related quantities. The initial photon with energy E_0 *is in the* $\hat{z}$ *direction.* θ *is the usual Compton scattering angle,* η *is the polarization vector of the initial photon, and* ϕ *is the azimuthal scatter angle on the* $\hat{x}$*-*$\hat{y}$ *plane.*

to the polarization vector results in a double peaked azimuthal scatter angle distribution with the expression below:
$dS/d\phi = (S/2\pi)[1 - Q\Pi \cos 2(\phi - \eta)]$
where Π is the fractional polarization. An example distribution with strong polarization signature is shown in Fig. 2. The minimum in the distribution gives the polarization angle. If Q of the instrument is known, the amplitude of the measured modulation can be used to obtain the polarization fraction Π.

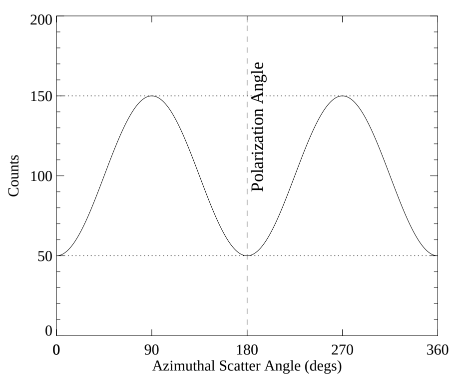

Figure 2. Example azimuthal scatter angle distribution for strongly polarized γ*-rays. The minimum in the distribution gives the polarization angle. For 100% polarized photons, the amplitude with respect to the average gives the modulation factor.*

Some of the other important quantities related to polarization measurements are the polarization sensitivity s_Π and the minimum detectable polarization (MDP). The polarization sensitivity is related to the continuum sensitivity through the modulation factor:
$s_\Pi = s/Q$ where s is the continuum sensitivity, and the minimum detectable polarization is defined as:
$\mathrm{MDP} = [\mathrm{n}_\sigma/\ (Q\ \mathrm{S})\ ]\ \sqrt{2(S+B)/T}$
where S is the source count rate, B the background count rate, T is the observation time, and n_σ is the desired signal-to-noise ratio..

3. SPI POLARIZATION

The coincidence (multiple) events in SPI can be used to measure the scatter angle distribution (see Fig. 3 for a representation of the SPI detector structure). It is not possible to determine the position of interaction in the SPI detectors. For each interaction, center to center angles are assumed (see Fig. 4). The uncertainty in azimuthal scatter angles are determined by the field of view of one detector relative to its neighbor. This effect reduces the modulation factor by $\sim$10%.

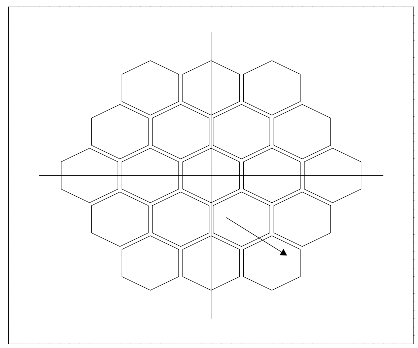

Figure 3. SPI detector formation. Multiple events define azimuthal scattering angles.

For energies less than 511 keV, the incoming photons predominantly scatter from the detector with the smaller energy deposition to the detector with larger energy deposition (Lingenfelter & Hua 1991), allowing six (center to center) scattering angles to be measured. For higher energies on the other hand, it is not possible to determine the ordering of the events uniquely, limiting the number of angles to only three.

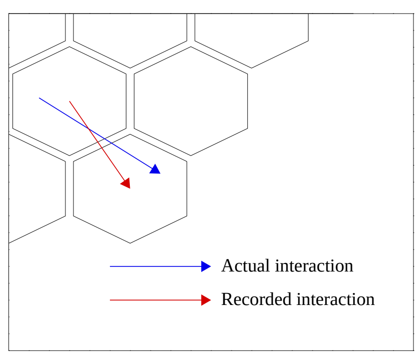

Figure 4. The actual interaction positions (shown the blue arrow) cannot be determined, and therefore center-center angles (shown with the red arrow) are assumed in the analysis.

4. MGEANT SIMULATIONS

MGEANT simulations with polarized beams (using "gleps" code developed by Marc Kippen and Mark McConnell, 2003) have been conducted to determine Q as a function of energy, and to test for potential applications. The azimuthal scatter angle distribution from one of the simulations is shown in Fig. 5. Photons of 300 keV and 100% polarized with a polarization angle of 135° were generated and sent in perpendicular to the detector plane. The resultant azimuthal scatter angle distribution was fitted using the azimuthal scatter angle distribution formula. This fit resulted in a modulation factor of Q=756 / 3536 = 22%, and η=137 ± 7 degrees, succesfully recovering the initial polarization angle.

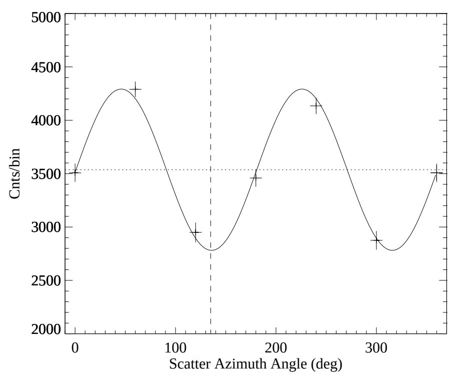

Figure 5. The azimuthal scatter angle distribution from 300 keV on-axis 100% polarized photons. The horizontal dashed line is the average rate and the vertical dashed line shows the minimum. The curve is the fit to the data.

We have repeated the simulation described above using photons at different energies to obtain the modulation factors as a function of energy. Fig. 6 shows the result of this work. The modulation factor for SPI is between ∼25% and 17% in 150-600 keV band and decreases with energy. This modulation rate is slightly higher than 17% in 200-500 keV band reported by Lei et al. (1997). IBIS modulation factors for the Compton mode as a function of energy are also shown in Fig. 6 for comparison.

5. APPLICATIONS

In this section, we investigate the feasibility of detecting polarization with SPI from different kinds of astrophysical objects. We concentrate on compact objects (bright neutron stars and black holes) and gamma-ray bursts.

Compact objects: The two obvious persistent sources to search for polarization are Cyg X-1 and Crab Nebula. The Crab in 150 - 300 keV band has a source count rate of S∼0.18 cts/s, and a measured background count rate of B∼14 cts/s in coincidence

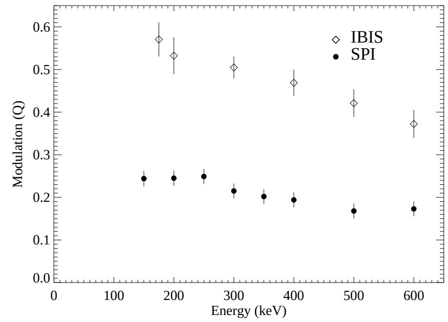

Figure 6. The modulation factors for on-axis photons as a function of energy for both SPI and IBIS Compton mode.

events. With a modulation factor Q of ∼0.2, the 3σ minimum detectable polarization in 1000 ks is 45%. This result is based solely on simulations and measured backgrounds, without taking any systematic errors into account. The dithering may also cause an increase in the MDP due to loss of source counts, however, it may help reducing systematic effects by mimicing rotation (especially if a dedicated dithering/rotating pattern is applied). The Cyg X-1 yields similar results. Although it is possible to put limits on γ-ray polarization fraction of Crab and Cyg X-1 using SPI, the results would be of marginal scientific interest.

Gamma-ray bursts A relatively strong GRB in the FOV of SPI has the best chance of measuring polarization, since, during the prompt emission of the burst, the counts will be source dominated. We have simulated polarized GRB emissions with typical spectral properties using MGEANT and tried to recover back the polarization properties.

Fig. 7 shows the simulated azimuthal scatter angle distribution of a moderately bright, on-axis GRB. The GRB has a fluence of $2.5 \times 10^5\,\mathrm{ergs\,cm^{-2}}$ in 50-300 keV, with this spectral parameters: E_{peak}=170 keV, α=-1, β=-2.4. The duration is 10 s. No background is added. The simulated beam is 100% polarized. The polarization angle is 135°. The spectral parameters given above results in a coincidence source count rate of 177 cts/s below 800 keV. After fitting, we found a modulation factor of ∼24%.

Compared to this simulated GRB, the background is still a significant fraction of the total counts (34 cts/s). To make the case more realistic, we added measured background events from a SPI empty field staring observation (Revolution 24). We randomly picked a 10 s portion of the empty field observation, add azimuthal scatter angles from those events to our simulated distribution in Fig. 7. We later used events 100 s before and 1000 s after the burst to estimate the background and subtracted it out. The final azimuthal scattering angle distribution is shown in Fig. 8. We obtained a modulation factor of ∼23% and polarization angle of 143 ± 10 degrees, and thereby recovered the original polarization pa-

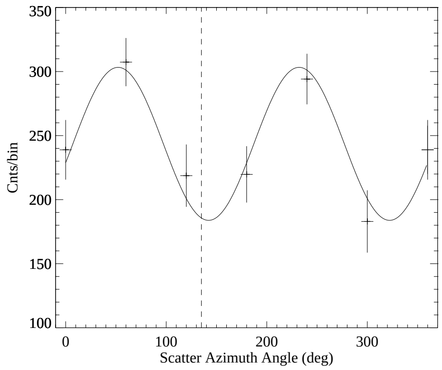

Figure 7. The simulated azimuthal scatter angle distribution of a moderately bright GRB with spectral parameters given in text. The dashed line shows the original polarization angle of 135°.

rameters. Note that, for this case, the 3σ MDP is ~50%.

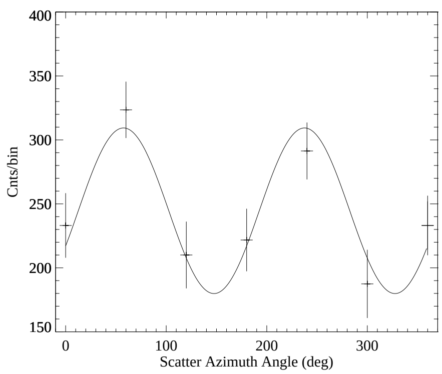

Figure 8. The simulated azimuthal scatter angle distribution of a moderately bright GRB in the SPI field of view with spectral parameters given in text. In this case, measured background scattering events were added, and then the background was estimated and subtracted using the data before and after the burst.

6. SUMMARY AND DISCUSSION

In this work we explored the possibility of detecting polarization with the SPI instrument on INTEGRAL. We showed that bright, hard gamma-ray bursts are ideal candidates to search for polarization with SPI. Although not discussed in this poster, IBIS instrument on INTEGRAL can also measure polarization using the Compton mode which has slightly better sensitivity due to higher modulation and lower background. IBIS+SPI can compliment each other for a GRB polarization measurement. This is especially important after the RHESSI measurement of high polarization fraction ($\Pi = 80 \pm 20$ %) from the prompt emission of GRB021206 (Coburn & Boggs 2003). With its better estimated modulation factor, and better sensitivity, SPI would have constrained the polarization fraction in the RHESSI detection of GRB021206 with less than 8% uncertainty.

Measuring polarization fraction of compact objects is more difficult. Since the emission is now background dominated, the systematic variations in the distribution of ME background becomes more important (see the accompanying proceeding by E. Kalemci). The background distribution does not vary much, and can be estimated using tracers. Therefore it may be possible to measure the polarization fraction of the Crab.

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