A SEARCH FOR GAMMA-RAY BURST POLARIZATION USING THE IBIS COMPTON MODE DATA

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ABSTRACT

The IBIS Compton mode data, which consists of events coincident between the ISGRI and PICsIT detector planes, is sensitive to gamma-ray polarization, due to the polarization dependence of the azimuthal distribution of Compton scatters. We present an analysis of the Compton mode data obtained during GRB041219a, a bright gamma-ray burst which occurred within the IBIS fully-coded field of view. We discuss the impact of data losses and accidental coincidence events during the burst. We place a preliminary upper limit of 65% on any linear polarization which persists throughout the burst.

1. COMPTON POLARIMETRY WITH IBIS

The IBIS Compton mode – events coincident between ISGRI and PICsIT, has polarimetry capabilities. The rate of events coincident between a given pixel in ISGRI and a given pixel (or multiple pixels) in PICsIT, depends on the polarization of the incident gamma-rays due to the polarization dependence of the Compton scattering cross-section. For an extensive review of Compton polarimetry see Lei, Dean & Hills [1].

For linearly polarized photons the Klein-Nishina cross section is

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{r_0^2}{2}\frac{E_1^2}{E_0^2}\left[\frac{E_1}{E_0} + \frac{E_0}{E_1} - \sin^2\theta(1 + cos2\phi)\right] \quad (1)$$

where r_0 is the classical electron radius, E_0 is the incident photon energy, E_1 the scattered photon energy, θ the photon scatter angle, and ϕ the azimuth of the scatter about the incident photon direction as measured from the incident electric polarization vector. The incident and scattered photons energies are related kinematically by

$$\frac{1}{E_1} = \frac{1}{E_0} + \frac{(1-\cos\theta)}{m_e c^2} \quad (2)$$

where m_e is the electron mass. Figure 1 shows the fractional amplitude of the sinusoidal modulation of the azimuthal scatter distribution given in equation 1.

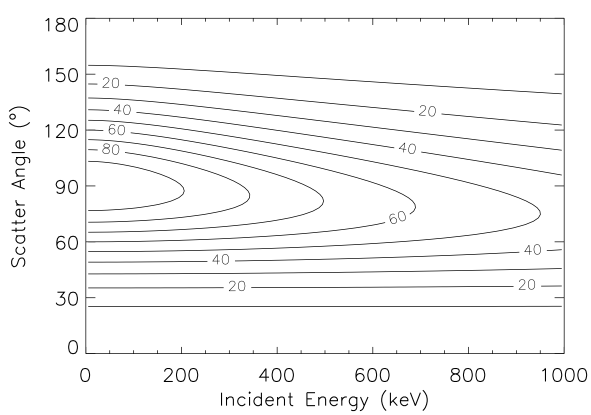

Figure 1. The fractional amplitude (%) of the azimuthal modulation of the Compton cross section for 100% linear polarization.

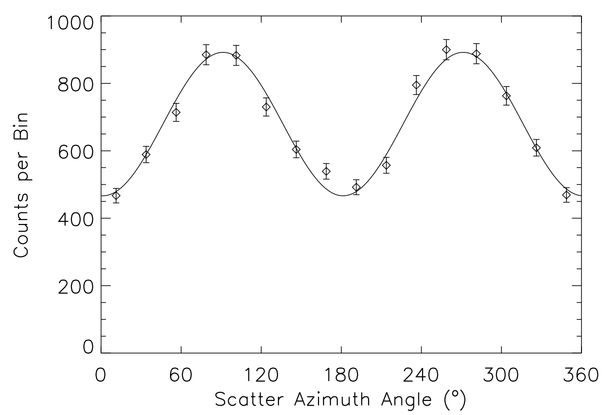

Figure 2. Azimuth angle distribution from a simulation of IBIS for 100% polarized 300 keV photons at normal incidence. The solid curve is a sinusoidal fit.

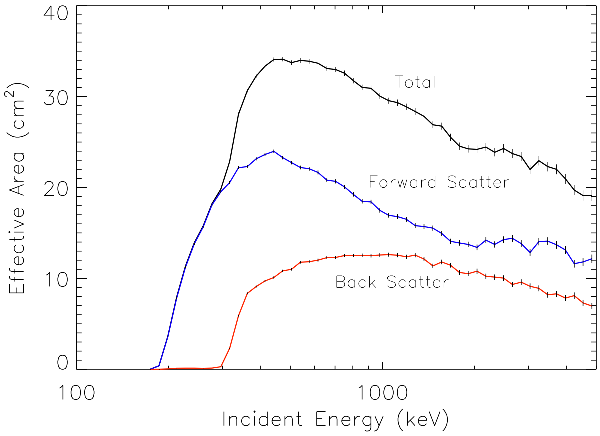

Figure 3. The effective area for the Compton Mode of IBIS, for normal incidence, excluding events with multiple detections in PICsIT.

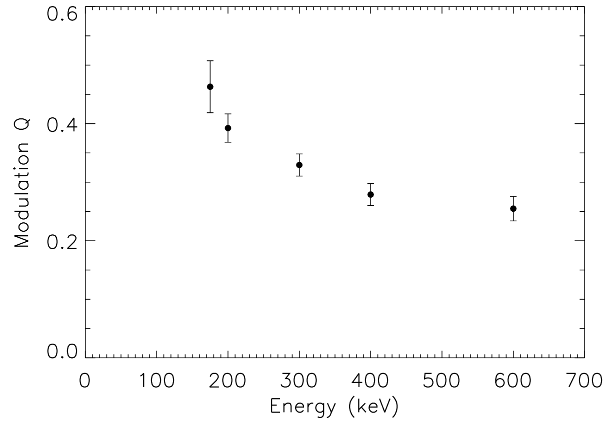

Figure 5. The azimuthal modulation amplitude Q versus the energy of 100% polarized photons, for ISGRI-PICsIT displacements of 10-15 cm.

Monte Carlo simulations were conducted to determine how this polarization dependence is reflected in the events coincident between ISGRI and PICsIT (the IBIS Compton mode). These simulations use the INTEGRAL Mass Model [2], and included the IBIS mask and detailed models of the IBIS instrument. Figure 2 shows the predicted distribution of the azimuth angle for the separation vector between the PICsIT and ISGRI pixel centers, for 100% polarized 300 keV photons normally incident on IBIS. No background is included. In our analysis we have used only events above 20 keV in ISGRI and above 170 keV in PICsIT that were detected in only one PICsIT pixel. Figure 3 shows the predicted effective area of the Compton mode with this data selection.

A coincident event can, near normal incidence, be characterized by the transverse distance, or displacement, between the ISGRI and PICsIT pixels centers and the azimuth angle (from the y axis say) of this displacement.

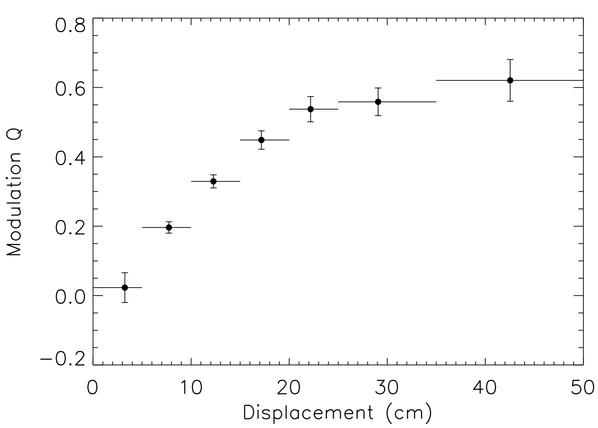

Figure 4. The azimuthal modulation amplitude Q versus the transverse displacement between ISGRI and PICsIT pixels of coincident events for 100% polarized 300 keV photons.

The azimuthal distribution for 100% polarized photons will be proportional to $1 - Q\cos 2(\phi - \phi_0)$, where Q is the fractional modulation amplitude and ϕ_0 is the azimuth of the incident polarization vector. Figure 4 shows how Q depends on the displacement distance for 300 keV incident photons. Figure 5 shows how Q depends on energies for events with displacements in the range of 10-15 cm (the ISGRI-PICsIT separation is 10.8 cm center-to-center).

2. GRB041219A

GRB041219a was detected with the INTEGRAL Burst Alert System (IBAS) on 2006 December 19 at 01:43 UT [3]. This bright, 500 s long burst was within the IBIS fully coded field-of-view, only 3.17° off axis. The burst was also observed by Swift/BAT during its science verification phase. At its peak its flux reached 43 photons cm$^{-2}s^{-1}$ [4], which played havoc with both the SPI and IBIS data systems.

In Figure 6 we compare the ISGRI light curve of GRB041219a with that from Swift, using for both instruments data from the 25-100 keV band, with 128 ms bins. No backgrounds are subtracted. The ISGRI light curve has been dead time corrected. During the high rate portions of the burst the ISGRI rates repeatedly drop to zero. These gaps, as well as loss within the 128 ms bins are caused by telemetry saturation, and FIFO event buffer overflows within IBIS. More than 90% of the events during the main peak (262–326 s after the precursor onset) were lost due to these throughput limitations and the high dead times caused by burst events in the veto detectors.

In Figure 7 we show a prediction of the IBIS compton mode light curve. This is for events with no multiple PICsIT interactions, with ISGRI energies in the 20–1000 keV range and PICsIT energies in the 170–5000 keV range. The Compton background was measured be-

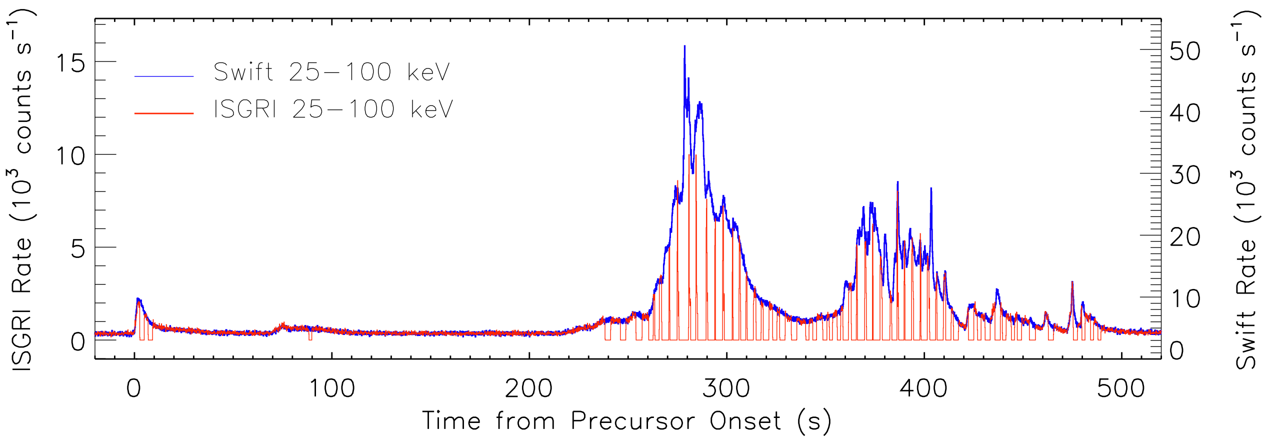

Figure 6. A comparison of the ISGRI and Swift light curves of GRB041219a in the 25-100 keV band.

fore the burst, and the burst induced true Compton rate is based on Monte Carlo calculation using the spectrum in the mean peak from McBreen et al. [4], scaled using the Swift light curve. To calculate the rate of accidental coincidences between ISGRI and PICsIT, the ISGRI and PICsIT rates were predicted using measured background rates, and source rates from the McBreen spectra folded through the detector responses scaled with the Swift light curve. Then accidental coincidence rate was calculated as

$$R_{acc} = \tau R_{ISGRI} R_{PICsIT} \tag{3}$$

where τ is the full coincidence window width of 3.576 μs [see 5].

In Figure 8 we show the measured IBIS Compton mode rate (top panel). Again there are data losses, however because of the Compton data's higher telemetry priority, these are lower than for ISGRI alone. In the bottom panel we show the fraction of events predict by our model that are true Compton photons from GRB041219a.

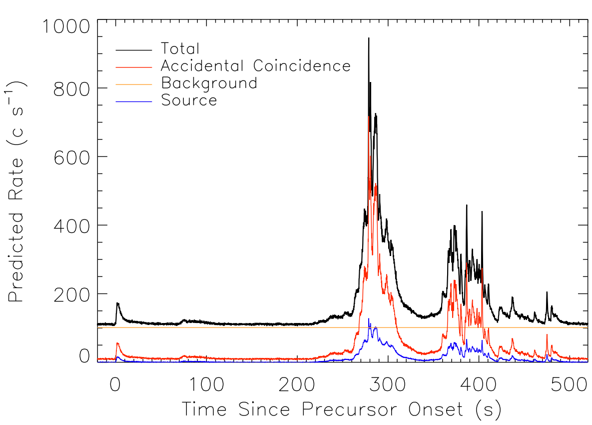

Figure 7. Predicted light curve of GRB041219a in the IBIS Compton mode data, excluding events interacting in multiple PICsIT detectors.

3. DATA ANALYSIS

Initially events were selected from the Compton mode data from time intervals where the predicted fraction of Compton events from the source was greater than 5%. The ISGRI energy range was restricted from 20-1000 keV, and the PICSIT energy restricted from 170 to 5000 keV. This resulted in 19758 events. The modeling already presented predicted that 11% of these are source events, 42% accidentals, and 47% Compton background.

To evaluate further cuts, we used Compton mode background from before the burst, our Monte Carlo simulation of the gamma-ray burst, and a simulation of the accidental coincidences. This simulation of the accidental coincidences uses PICsIT single pixel events from prior to the burst (no PICsIT event-by-event data was collect during the burst) which were randomly combined with ISGRI events from during the burst.

To evaluate the consistency of each event with a Compton scattered source photon, we make χ^2 fits of the Energy deposits in ISGRI and PICsIT using the kinematic equation 2), and assuming the full energy of the initial photon was deposited. These fits were made for both the forward scattering case, and the back scattering case. The adjustable parameters in these fits are the incident energy E_0, and the scatter angle, which was allowed to vary over the full range possible given the ISGRI and PICsIT pixels involved, and the well determined direction of GRB041219a. Our data selection required $\chi^2_{forward} < 5$ and that the ISGRI pixel be exposed to the burst (PIF> 0.12) or that $\chi^2_{back} < 5$ and the PICsIT pixel be exposed to the burst (PIF> 0.25).

From background data and our simulations we predict that these cuts should reduce the Compton background events by 85%, and the accidental coincidences by 85%, while retaining 55% of the source photons. The cuts resulted in 3089 remaining events, of which about a third are source photons, a third accidentals, and a third Compton background.

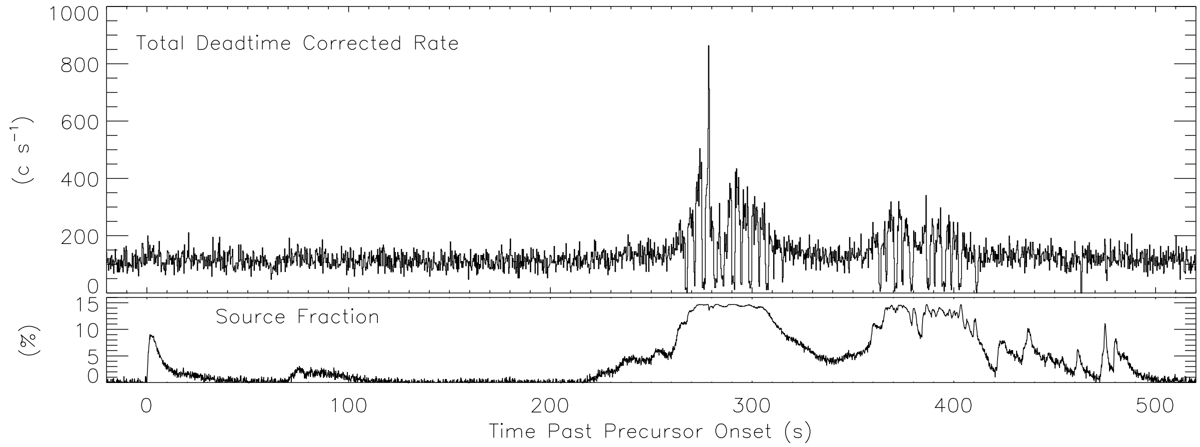

Figure 8. Top: The light curve of GRB041219a observed in the IBIS Compton mode, excluding events interacting in multiple PICsIT detectors. This uses 128 ms bins with the rates dead time corrected. Bottom: The inferred fraction of GRB photons in the Compton mode data.

Figure 9 shows the azimuthal distribution found for the selected Compton mode data (top panel). We also show the distribution for the simulated GRB photons with the same selections, the simulated accidental coincidence events, and the Compton background data. There is no detectable sinusoidal modulation with two periods per cycle as expected from linear polarization. We can place a 3σ upper limit of 4% on the amplitude of such a modulation in the selected Compton mode data.

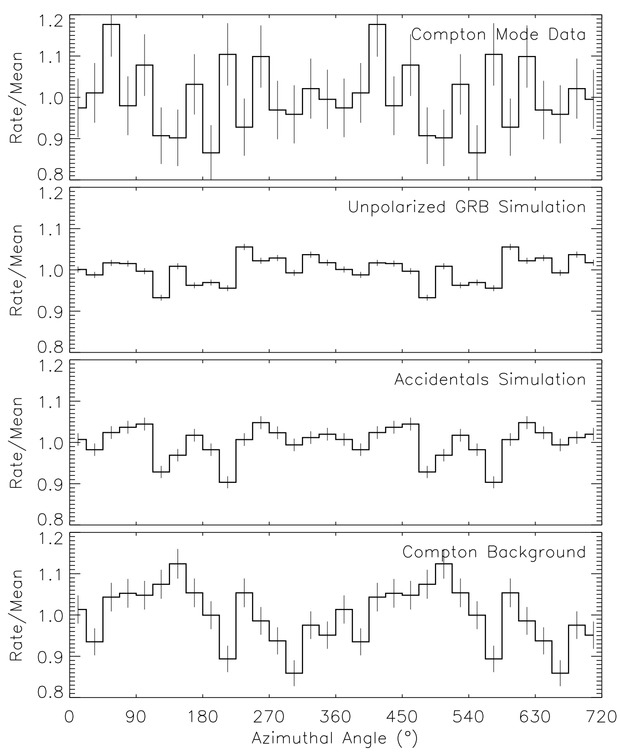

Figure 9. Azimuthal distributions for the selected Compton mode data, and for measurements or simulations of the components of this data.

4. RESULTS

If our estimate of fraction of source photons in the data is correct, this gives an upper limit of 12% modulation in the source photons. We estimate an average modulation factor Q of 0.20 for the burst photons from the simulations. We can therefore place an upper-limit of 65% on the burst polarization.

However our need to derive the intrinsic ISGRI and PICsIT rates from measurements of other instruments, expected deviations of the accidental coincidence rate from equation (3) at high rates, rate dependent losses of true Compton events in the ISGRI-PICsIT coincidence determination, and uncertainties in the deadtimes at high rates, all limit the accuracy of our estimate of the source photon fraction in the selected data. Our upper limit must be considered preliminary until these issues are addressed.

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