X-Ray Albedo Polarimetry and the Search for Polarization in BATSE Gamma-Ray Bursts

M. McConnell, D. Forrest, W.T. Vestrand

Space Science Center, University of New Hampshire, USA

Abstract

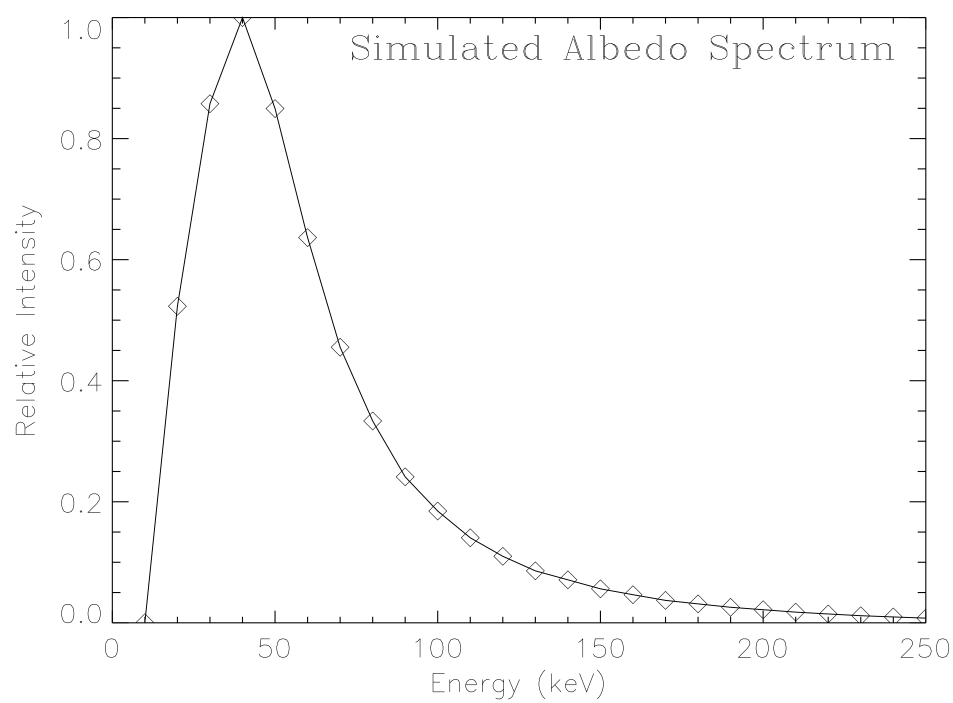
We describe a technique for measuring the polarization of hard X-rays from a celestial source based on the angular distribution of that portion of the flux which is scattered off the top of the Earth's atmosphere. The scattering cross section depends not only on the scatter angle itself, but on the orientation of the scatter angle with respect to the incident polarization vector. Consequently, the distribution of the observed albedo flux will depend on the direction and the polarization properties (i.e., the level of polarization and polarization angle) of the source. Since the albedo component can represent a relatively large fraction (up to 40%) of the direct source flux, there will generally be sufficient signal for making such a measurement. The sensitivity of this approach is therefore dictated by the effective area and the ability of a detector system to 'image' the albedo flux. The 4π coverage of the BATSE detectors on the *Compton Gamma-Ray Observatory* provides an opportunity to measure both the direct and the albedo flux from a given transient event (either a gamma-ray burst or solar flare). Although the BATSE design (with its large field-of-view for each detector) is not optimized for albedo polarimetry, we have nonetheless investigated the feasibility of this technique using BATSE data.

X-Ray Albedo Polarimetry

- In a transient event, a significant fraction of the hard X-ray flux incident on the Earth's atmosphere (up to $\sim 50\%$) is reflected via Compton scattering.
- If the incident flux is linearly polarized, there will exist preferred directions for the scattering. In particular, the scattered photons will tend to be emitted in directions which are perpendicular to the incident electric field vector.
- This tendency will influence the distribution of the albedo flux across the disk of the Earth as seen from an Earth-orbiting satellite.
- A measurement of the albedo flux distribution (in conjunction with additional information about the source direction and spectrum) can provide information regarding the bulk linear polarization of the incident flux.

Simulating the Albedo Flux Distribution

- Modified version of GEANT has been used to study the distribution of the albedo flux in the case of a linearly polarized source.
- The simulations assume an incident E^{-2} power-law spectrum extending from 10 keV up to >1 MeV.
- For such an incident spectrum, the albedo flux peaks near 50 keV, with most of the flux at energies below 200 keV.

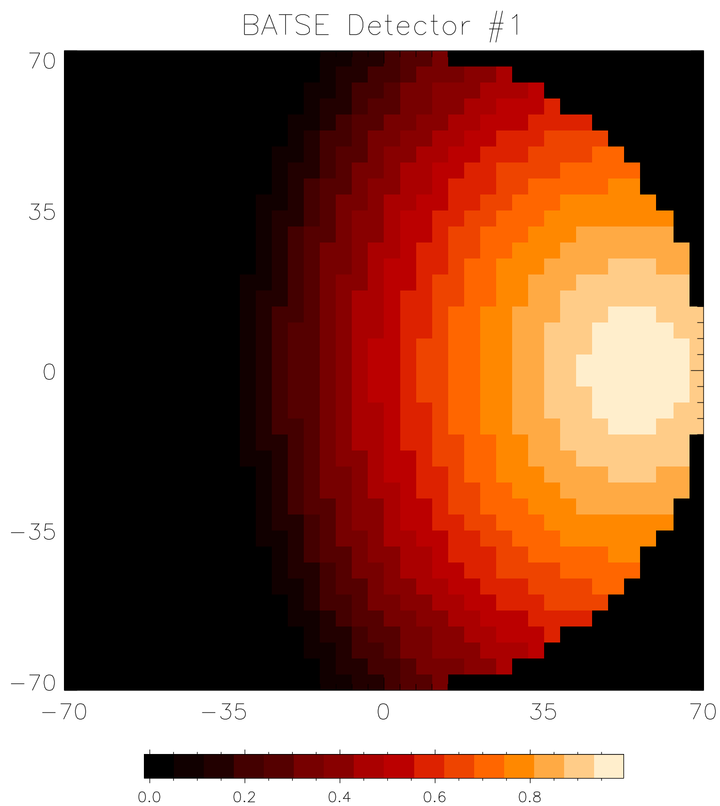


Estimating the BATSE Polarization Sensitivity

BATSE sensitivity curves have been generated based on the following:

- The CGRO z-axis points to the local zenith. The four downward-pointing detectors are used to define the albedo response.
- We assume an LAD angular response which falls to zero at 90° and follows the form of that in the 50-100 keV energy range.
- The direct source flux is neglected. Leakage is assumed to be zero.
- A typical BATSE background level is assumed ($\sim 10^5$ counts in burst interval).
- The sensitivity is based on a χ^2 comparison of the detector responses for the polarized versus unpolarized simulations.

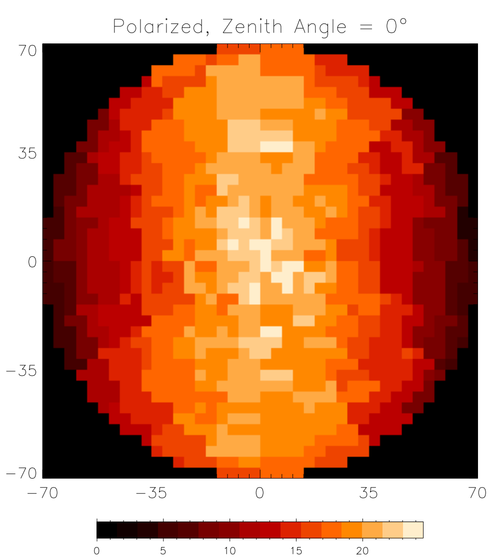
Angular Response of BATSE Large Area Detectors

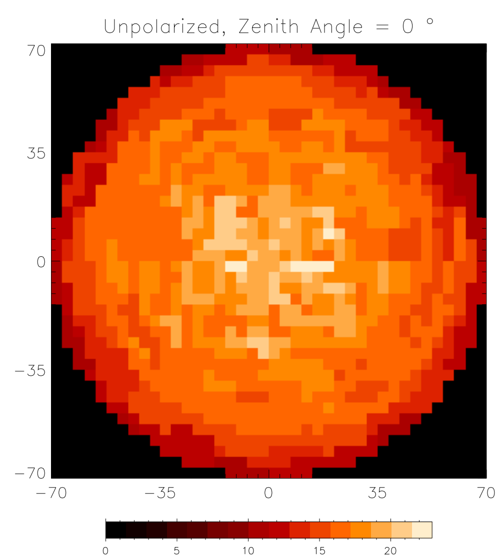


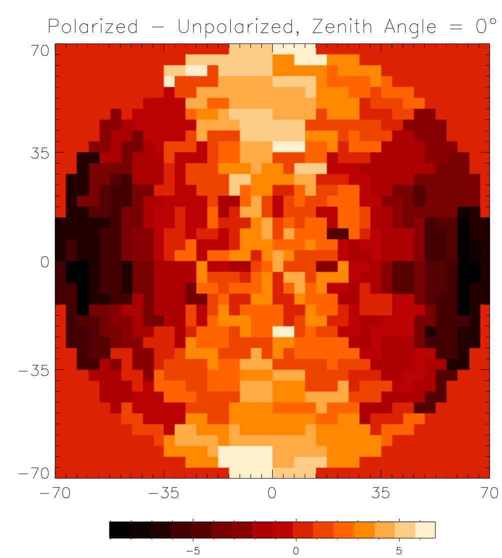
This figure represents the relative response of a BATSE Large Area Detector (LAD) as projected onto the visible disk of the Earth. (As seen from low Earth orbit, the Earth subtends a radius of $\sim 70°$.) The pointing direction of this detector is offset $54°$ from the nadir.

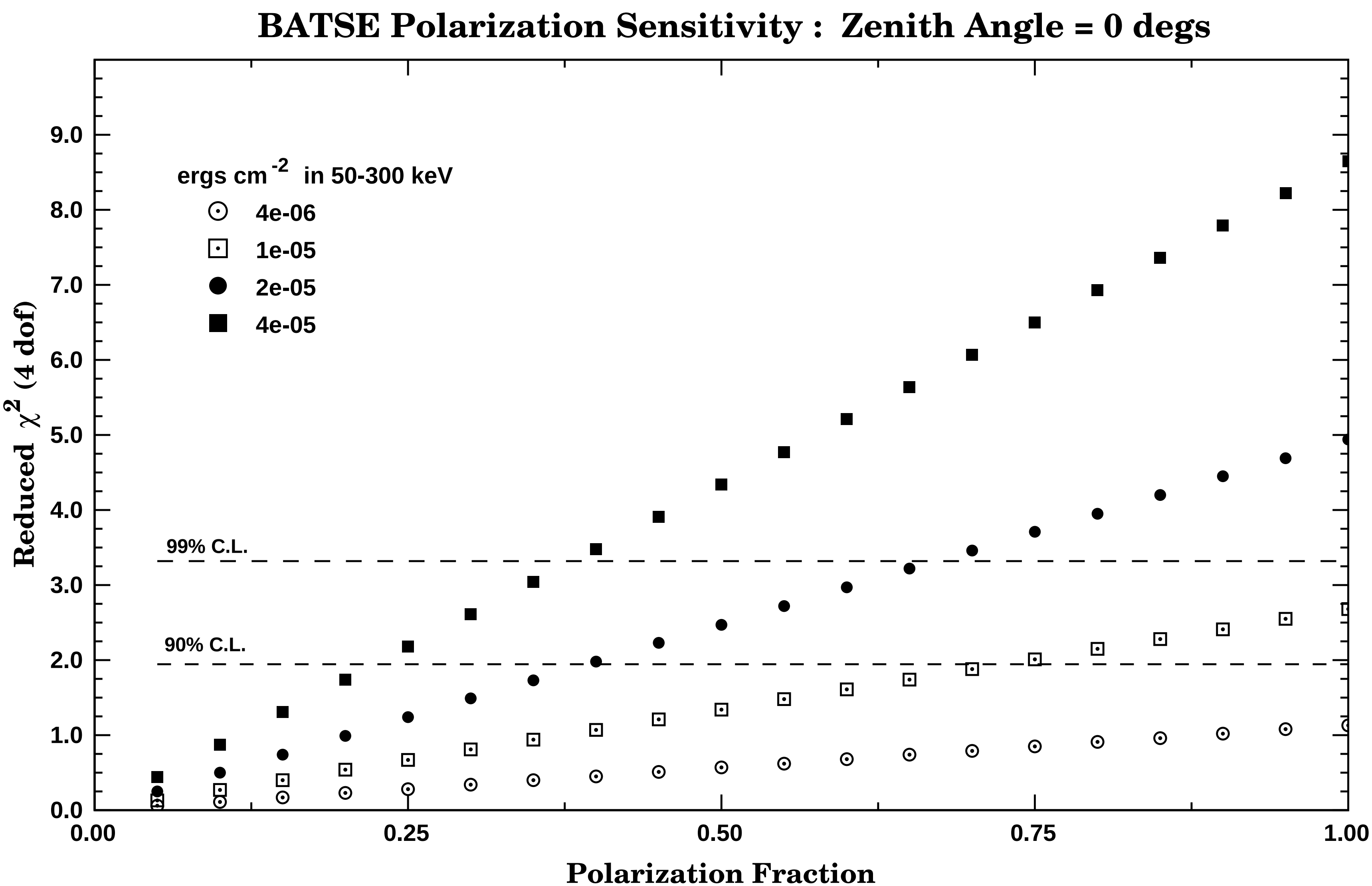
Incident Zenith Angle = 0°

These images represent the simulated distribution of the albedo flux across the visible disk of the Earth (which subtends a radius of $\sim 70°$ as seen by BATSE). In this case, the source is located at the zenith (along the z-axis) and the polarization vector lies in the x-z plane. Note that the scattered photons tend to be emitted perpendicular to the polarization vector.



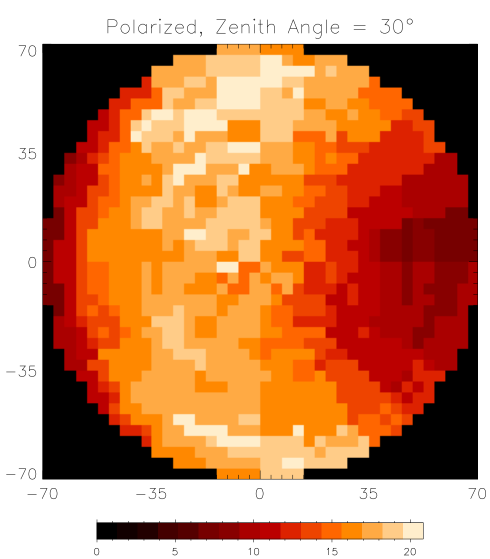


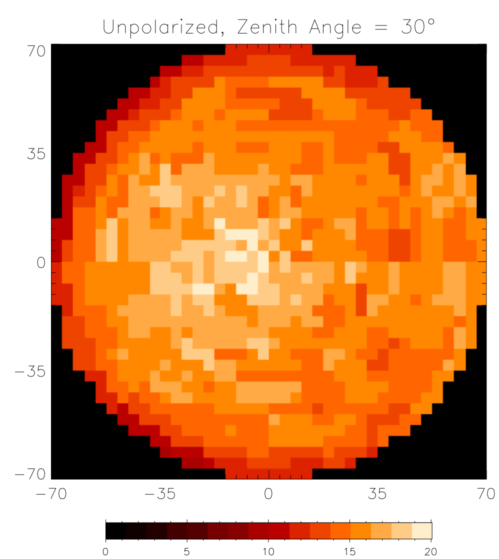


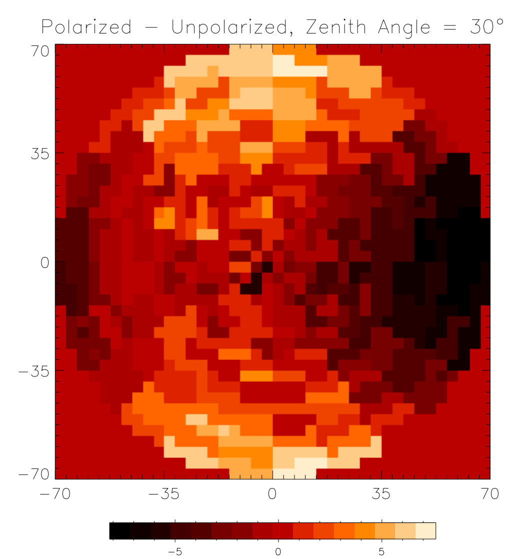

BATSE Polarization Sensitivity : Zenith Angle = 0 degs
Reduced χ^2 (4 dof)
Polarization Fraction
ergs cm^{-2} in 50-300 keV
4e-06
1e-05
2e-05
4e-05
99% C.L.
90% C.L.
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
0.00
0.25
0.50
0.75
1.00

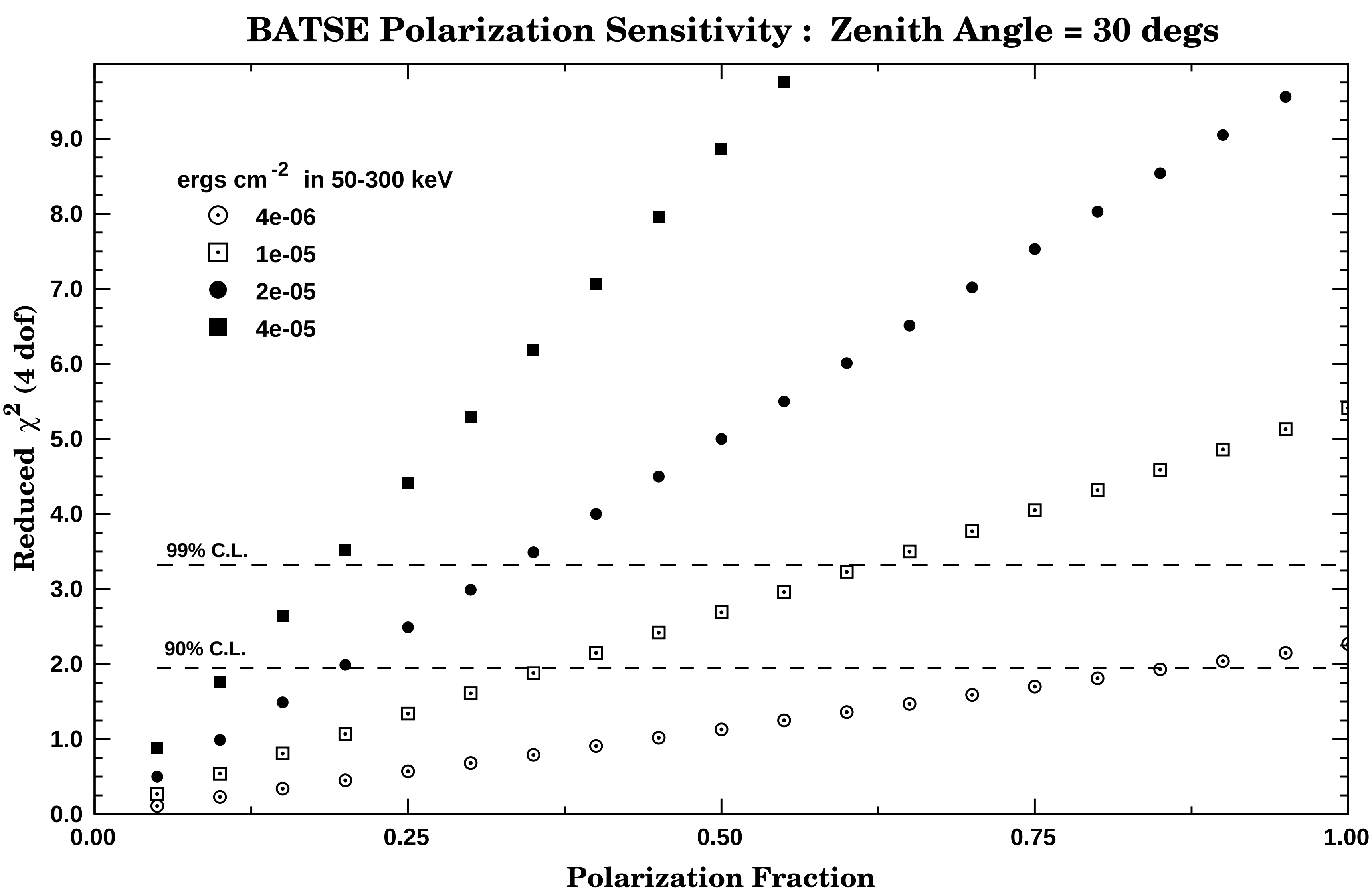
Incident Zenith Angle = 30°

These images represent the simulated distribution of the albedo flux across the visible disk of the Earth (which subtends a radius of $\sim 70°$ as seen by BATSE). In this case, the source lies in the +x/+z plane, at a zenith angle of 30°. The polarization vector lies in the x-z plane. Note that the distribution is now somewhat skewed by the larger zenith angle of the source.





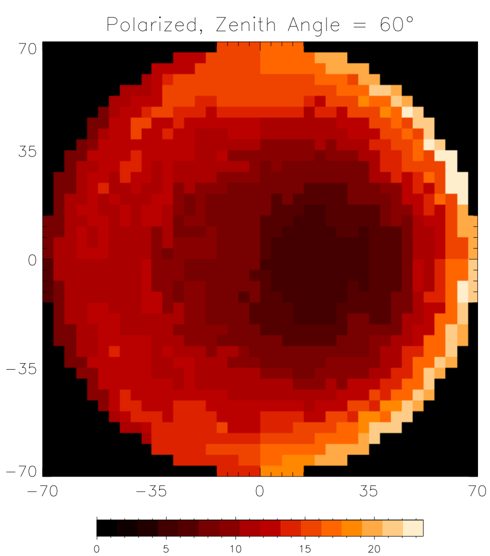


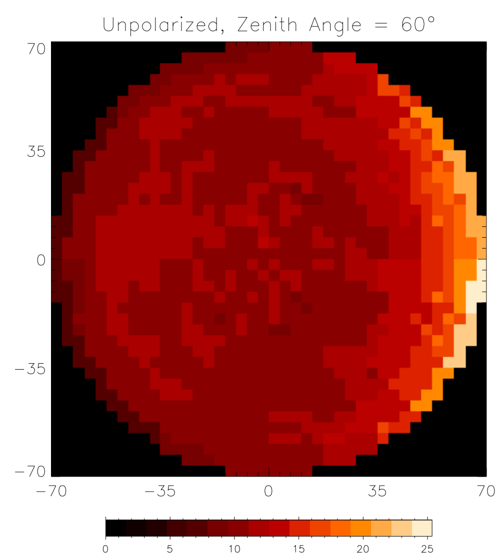


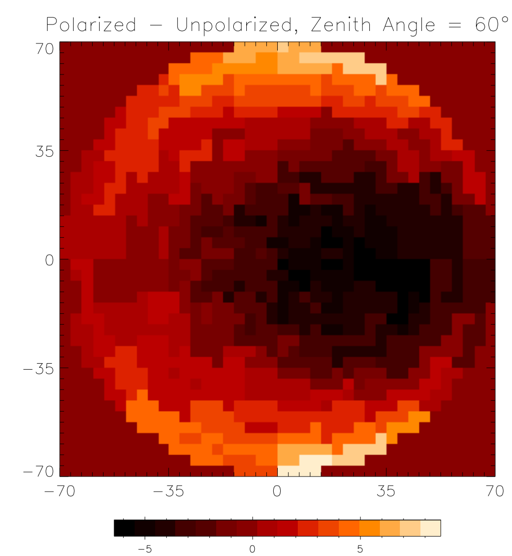
BATSE Polarization Sensitivity : Zenith Angle = 30 degs
ergs cm -2 in 50-300 keV
4e-06
1e-05
2e-05
4e-05
99% C.L.
90% C.L.
Reduced χ2 (4 dof)
Polarization Fraction
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
0.00
0.25
0.50
0.75
1.00

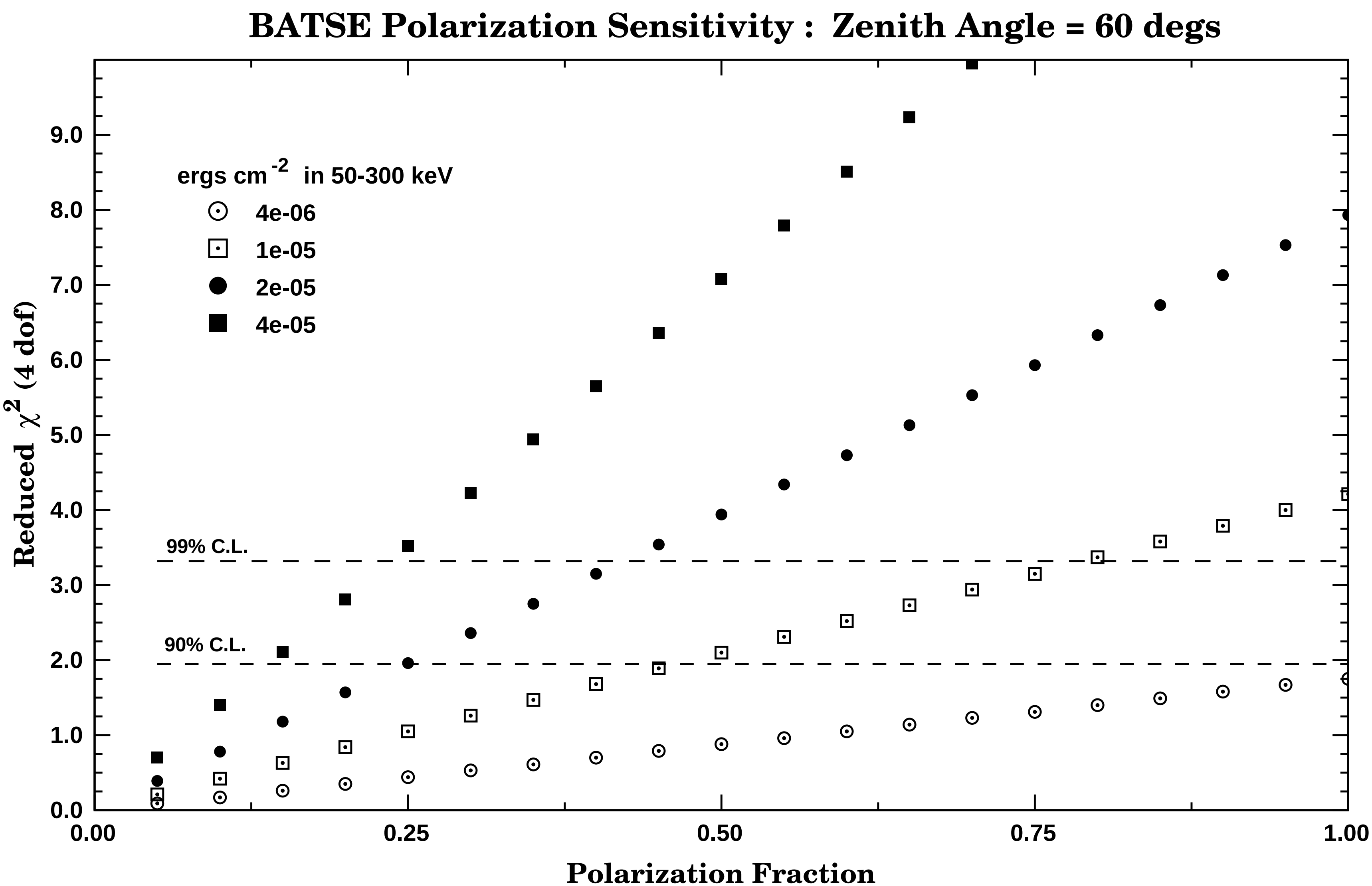
Incident Zenith Angle = 60°

These images represent the simulated distribution of the albedo flux across the visible disk of this Earth (which subtends a radius of $\sim 70°$ as seen by BATSE). In the case, the source lies in the +x/+z plane, at a zenith angle of 60°. The polarization vector lies in the x-z plane. Here we begin to see effects which result not from the polarization of the incident flux, but rather from the larger probability of forward scattering which is inherent in the Compton process.








BATSE Polarization Sensitivity : Zenith Angle = 60 degs
ergs cm -2 in 50-300 keV
4e-06
1e-05
2e-05
4e-05
99% C.L.
90% C.L.
Reduced χ2 (4 dof)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
0.00
0.25
0.50
0.75
1.00
Polarization Fraction

BATSE Polarization Sensitivity

BATSE appears capable of setting constraints on burst polarization for bursts with fluence in excess of $\sim 10^{-5}$ ergs cm^{-2}.

In the BATSE 2B catalog, there are about 50 events with 50-300 keV fluence level greater than $\sim 10^{-5}$ ergs cm^{-2}.

BATSE Data Analysis

- We attribute all of the observed counts in those detectors facing away from the source ($\theta > 90^\circ$) to the albedo flux.
- The observed count distribution amongst those four detectors can be compared to the (simulated) unpolarized case. This requires information (or assumptions) about the source direction, source spectrum, and spacecraft geometry.
- If the data are inconsistent with an unpolarized source, then one can proceed to determine the level of polarization as a function of polarization angle for that event. This involves a comparison of the data with a series of simulations.
- A more complete analysis would include data from all eight LAD detectors and would incorporate the response of the detectors to the direct source flux.

A Null Test Using Weak Bursts

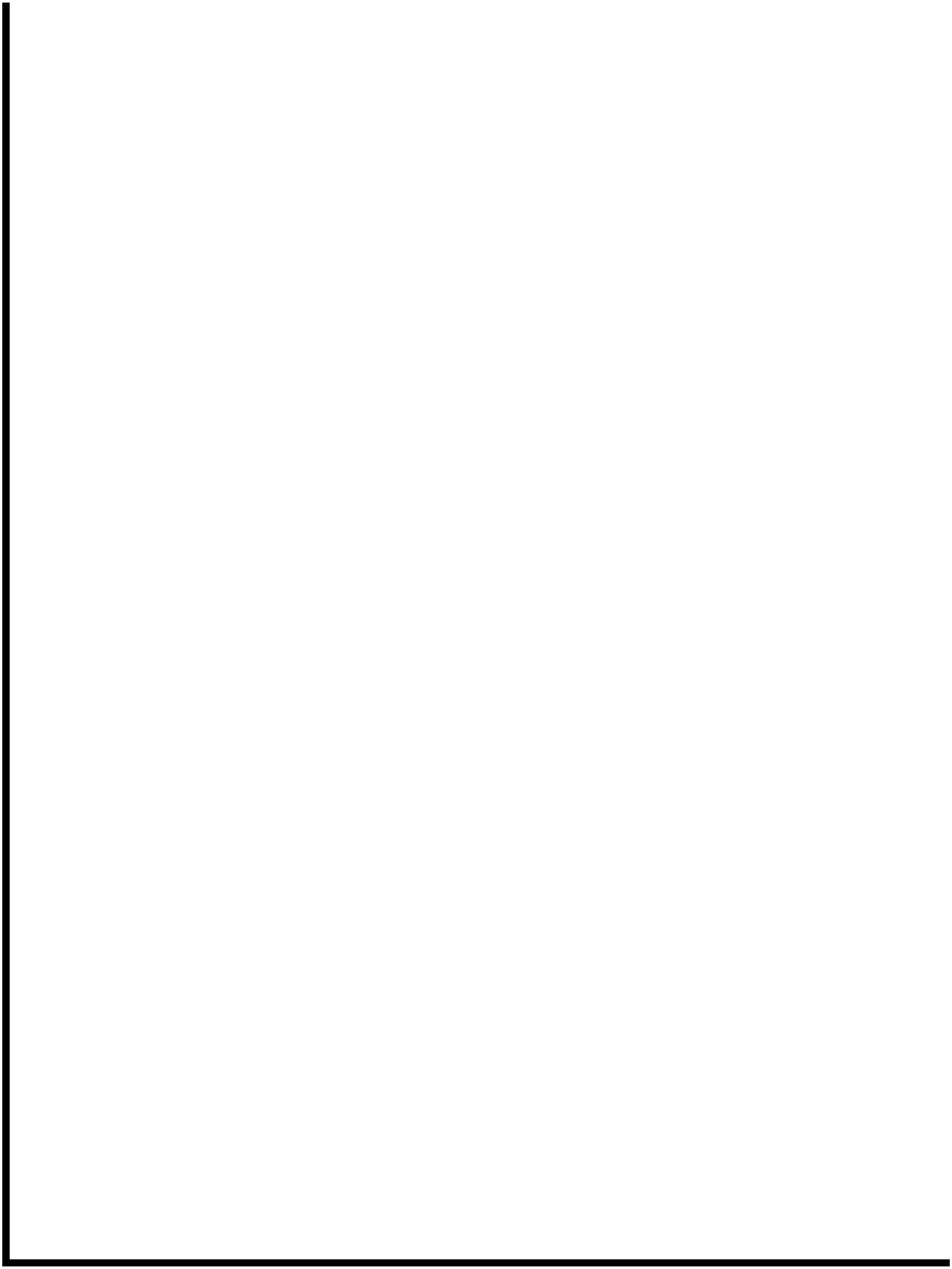
- We have chosen two events of moderate intensity ($\sim 4 \times 10^{-6}$ ergs cm^{-2}) for which no measurable polarization is to be expected.
- In each case, we have selected those four LADs which are $> 90^\circ$ from the burst direction.
- We have compared the observed counts versus the simulated number of counts for an unpolarized source at the given position and fluence level.
- The discrepancy in overall normalization is not completely understood at this time, but may arise from incorrect assumptions about the source spectrum.
- There is good agreement between measured and simulated data in terms of the fractional counts in each detector.

Analysis of 2B 911104

Trigger No.	999			
Zenith Angle	59.9°			
fluence (50-300 keV)	3.3×10^{-6} ergs cm^{-2}			
	observed		*simulated*	
counts	*absolute*	*fractional*	*absolute*	*fractional*
det A (#4)	2963±424	.169±.024	6138	.189
det B (#5)	1375±404	.078±.023	3008	.092
det C (#6)	8563±389	.488±.022	14387	.442
det D (#7)	4643±405	.265±.023	9027	.277
χ^2_ν	1.40 (based on fractional counts)			
$P(> \chi^2_\nu)$	0.23 (based on fractional counts)			

Analysis of 2B 920307

Trigger No.	1467			
Zenith Angle	27.1°			
fluence (50-300 keV)	3.9×10^{-6} ergs cm^{-2}			
	observed		*simulated*	
counts	*absolute*	*fractional*	*absolute*	*fractional*
det A (#0)	3026±582	.120±.023	4359	.085
det B (#2)	5708±585	.226±.023	9905	.192
det C (#4)	6429±575	.255±.023	14199	.275
det D (#6)	10062±532	.399±.021	23121	.448
χ_{ν}^2	2.68 (based on fractional counts)			
$P(\chi_{\nu}^2)$	0.03 (based on fractional counts)			



Future Work

Our present effort is concentrated on the establishment of a valid analysis technique. In particular...

- Resolving the normalization discrepancy.
- Improving the simulations (i.e., better statistics).
- Generating a more complete set of simulations to cover the necessary parameter space (zenith angle, polarization fraction, polarization angle and incident spectral shape).
- Incorporating a more precise LAD response, including in-flight energy calibrations.
- Incorporating all eight detectors into the analysis.

Once our analysis technique is established and verified, we will begin the systematic search for polarization in the BATSE database.

Summary

- X-ray albedo polarimetry is a potentially useful technique for studying the polarization of transient hard X-ray/γ-ray sources.
- BATSE appears to be capable of setting constraints on the polarization parameters in bursts whose 50-300 keV fluence is greater than $\sim 10^{-5}$ ergs cm^{-2}. This includes a a number of γ-ray bursts and solar flares.
- We are presently developing the necessary tools and procedures for a systemtic search of the BATSE database for evidence of polarization.