

## 1.0 INTRODUCTION

One of the four fundamental properties of electromagnetic radiation is its polarization. Although this property has been exploited extensively for astrophysical studies at longer wavelengths, there have been no serious attempts to measure polarization from sources with  $E > 30$  keV. In previous work, we demonstrated how one might use the radiation which is backscattered from the Earth's atmosphere to study source polarization. Based on simulations, we have estimated the BATSE sensitivity to polarization in  $\gamma$ -ray bursts (GRBs) and find significant sensitivity to polarization levels below 20% for fluences in excess of  $4 \times 10^{-5}$  ergs  $\text{cm}^{-2}$  (McConnell et al. 1996a); in the latest BATSE catalog (27-May-1997), 23 events exceed this fluence level. A similar sensitivity holds for solar flares (McConnell et al. 1996b), but given the larger fluences of some solar flares, we can anticipate greater polarization sensitivity. Transient events are especially susceptible to polarization measurement in this manner because they permit a straightforward source-on / source-off measurement. Another time varying signal which lends itself to polarization measurement is that observed from pulsars. *Here we propose to continue our efforts to measure the polarization properties of  $\gamma$ -ray bursts, solar flares and pulsars using BATSE data.* This work would emphasize improved simulations, a more careful assessment of sources of systematic uncertainty and a more detailed analysis of individual sources. In addition, *we would extend the capabilities of our simulation code to explore the potential for direct polarization measurements with the BATSE LAD detectors, based on the off-axis sensitivity dependence on incident polarization angle.*

The phenomenon of the GRBs has remained a mystery ever since their discovery some 25 years ago. Although observations suggest that the soft  $\gamma$ -ray repeaters are associated with supernova remnants (e.g., Kulkarni and Frail 1993), the origin of the classical bursters remains a subject of much debate. Although recent discoveries of apparent optical and radio counterparts may possibly shed some light on the distance scale, there nonetheless remains much work to more completely understand the nature of these intriguing sources. The importance of polarization measurements is simply that they may add one more useful clue to be included in any theoretical studies (regardless of the distance scale). Although the published literature on the subject of polarization in bursts is limited (most certainly driven, in part, by a lack of observations), there appears to be a general consensus that such measurements would be useful (e.g., Hurley 1992; Lund 1992). In principle, *polarization measurements would provide information on both the emission mechanism (e.g., bremsstrahlung vs. synchrotron) and on the geometry of the emitting region (e.g., as defined by the magnetic field).*

Polarization measurements of solar flares can be used to search for anisotropies in the accelerated electron distribution. The usual method for assaying the anisotropy is to search for evidence of directivity in the flare radiation at  $E > 100$  keV, where a greatly reduced Compton reflectivity and increased directionality of the bremsstrahlung cross-section make relatively strong radiation anisotropies a possibility at these energies. A statistical analysis of the disk center-to-limb variations in flare frequency and spectra provided relatively strong evidence for directed emission from flares (Vestrand et al. 1987; Bogolov et al. 1985). Quantifying the magnitude of the directivity from these statistical measurements is difficult, since the results only represent an average for the flare sample. Different flaring regions are not likely to have identical geometry. Nor are individual flares likely to have time independent electron distributions. Therefore, to do detailed studies of the particle distributions, one needs a technique that can measure time dependent anisotropies on a flare by flare basis. Data from one such approach to this problem, specifically stereoscopic observations (e.g., Catalano and Van Allen, 1973; Kane et al. 1982), are not as yet of sufficient quality to reach any firm conclusions regarding directivity (McTiernan and Petrosian 1990). Polarization measurements represent another approach to directivity measurements in individual solar flares. Measurements of flare X-ray polarization at  $E < 25$  keV (Tindo et al. 1972; Nakada, Neupert and Thomas 1974; Tindo et al. 1976; Tramiel, Chanan and Novick 1984) tend to suggest levels of polarization (typically,  $< 5$ -10%) that are consistent with the predictions for purely thermal emission that contains an admixture of polarized backscattered radiation (Bai and Ramaty 1978). This thermal component tends to dominate the emission from all flares at energies below about 25 keV. Chanan, Emslie and Novick (1988) have pointed out that, because of this thermal "contamination", effective polarization measurements can only be performed at higher energies. Furthermore, the observational evidence for directivity (Vestrand et al. 1987) requires the presence of linear polarization, perhaps in excess of 20% (e.g., Bai and Ramaty, 1978; Emslie and Vlahos 1980; Leach and Petrosian, 1983), in the bremsstrahlung emission at energies  $> 100$  keV. *BATSE has the potential of making polarization measurements in an energy range above the thermal and solar backscattered energy region. Such measurements will place important constraints on the energetic electron geometries, thus complementing the spectral measurements.*

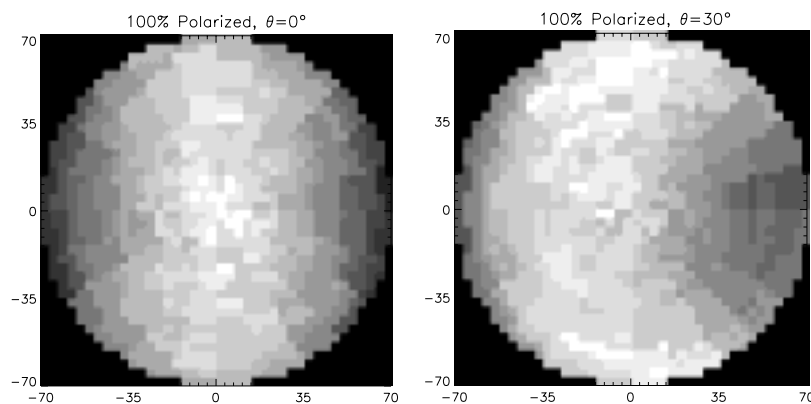
Polarization measurements would also be useful in studies of hard X-ray emission from pulsars. Data returned from the polarimeter aboard OSO-8 showed polarization levels of  $\sim 19\%$  in the 2.6–5.2 keV flux from the Crab Nebula (Weiskopf et al. 1978). These results were extremely important in firmly establishing synchrotron radiation

as the X-ray emission process responsible for the un-pulsed (nebular) component of the Crab's emission. Theoretical modeling of pulsar magnetospheres suggest that polarization measurements of pulsars may provide clues as to the exact nature of the radiation process (e.g., Mészáros et al. 1988; Romani and Yadigaroglu 1995).

At present, there is no  $\gamma$ -ray experiment in operation whose major emphasis is the measurement of polarization. The COMPTEL instrument on CGRO (Schönfelder et al. 1993), for example, has limited capabilities for detecting polarized emission from sources within its FoV (Vestrand et al. 1997). Although future instruments (such as INTEGRAL) may have significant sensitivity to polarized radiation, their sensitivity will be limited to a rather narrow FoV (which will necessarily exclude the Sun). Hence, the utility of these experiments for studying emission from GRBs and solar flares may be limited.

## 2.0 X-RAY ALBEDO POLARIMETRY WITH BATSE

A measurement of the linear polarization of a celestial source of hard X-rays can, in principle, be made by measuring the angular distribution of the albedo flux, i.e., the source flux which is scattered from the Earth's atmosphere prior to reaching the detector. The concept of *albedo polarimetry* is based on the fact that a Compton scattered photon tends to be ejected at right angles to the incident electric field vector. The atmosphere, as seen from an orbiting satellite, presents a wide range of possible scatter angles for a given incident source direction. The photon scatter angle will depend on the look direction. Hence, the intensity distribution of the albedo flux will exhibit an angular distribution that will depend on the (energy-averaged) polarization properties of the incident source radiation. For the case of an orbiting detector, the distribution of the scattered albedo flux across the top of the atmosphere will depend on: 1) the angular height of the source above the Earth's limb; 2) the level of linear polarization of the source flux; and 3) the orientation of the bulk polarization vector of the source flux. *Given the direction of the source, the linear polarization properties can be determined from a measurement of the albedo flux distribution.*



*Figure 1: Spatial distribution of the albedo flux (10 keV to 1 MeV) for an  $E^{-2}$  spectrum incident at  $0^\circ$  (left) and  $30^\circ$  (right) from the zenith. The plane of polarization lies in the horizontal direction.*

Consider the case of a transient event observed at the local zenith. For an unpolarized source, the albedo flux will be uniformly distributed across the observed disk of the Earth. For a linearly polarized source, however, the observed albedo flux will exhibit an asymmetry about the azimuthal direction. This asymmetry will take the form of a sinusoid dependence on the azimuthal angle. The magnitude of these variations represents a measure of the polarization fraction, while the plane defined by the azimuthal minima corresponds to the plane of

linear polarization in the incident flux. For sources which are located away from the local zenith, there will be asymmetries introduced even in the case of an unpolarized source. For example, for events which are close to the Earth's limb, the higher probability of forward scattering will result in a limb-brightening effect in the general direction of the source. In addition, for events with a zenith angle in the range of  $70^\circ$ - $110^\circ$ , not all of the visible atmosphere is exposed to direct source flux. A precise measurement of polarization will require that all of these effects be properly accounted for.

We have modeled the entire scattering process with simulations based on a version of GEANT that has been modified to track photon polarization. For a source at the local zenith, the fraction of 150 keV flux reflected off the atmosphere is  $\sim 40\%$ . For an incident  $E^{-2}$  spectrum, the spectrum of the scattered flux peaks at  $\sim 75$  keV. Examples of the simulated spatial distribution of the scattered flux are shown in Figure 1, which shows the intensity of the scattered flux across the visible disk of the Earth (subtending a half-angle of  $\sim 70^\circ$  at CGRO altitudes) for a 100% polarized source at zenith angles of  $0^\circ$  and  $30^\circ$ . The asymmetries seen here are due entirely to polarization effects.

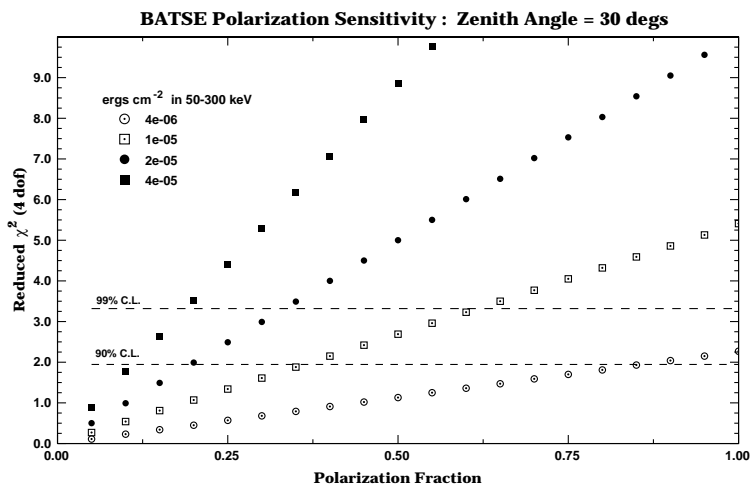


Figure 2: Sensitivity estimate for polarization of a burst at a zenith angle of  $30^\circ$ . The burst spectrum is an  $E^{-2}$  power-law and these data represent the integrated 0.01–1.0 MeV response.

two sets of numbers determines whether or not polarization is present. An example of our sensitivity estimates is given in Figure 2. These data show that source polarization can be detected (at the 99% confidence level) for a burst with a 50–300 keV fluence of  $4 \times 10^{-5}$  ergs  $\text{cm}^{-2}$  and a polarization fraction greater than about 15%. (As of 27-May-1997, there are 23 events in the BATSE catalog with fluence levels  $>4 \times 10^{-5}$  ergs  $\text{cm}^{-2}$ .)

A complete description of the BATSE response requires an understanding of: 1) the direct source flux; 2) the scattered albedo flux; and 3) the flux leakage through the spacecraft. The source-detector-earth geometry will dictate to what extent a given source will be susceptible to polarization measurements. (For example, the maximum polarization sensitivity is achieved for a source at a zenith angle of  $30^\circ$ .) Furthermore, real asymmetries may also be masked by the small, but inevitable, differences among the eight BATSE detectors. For these reasons, a complete study must include a study of the various systematic effects which are inherent in the data. Although the albedo component is considered a part of the BATSE response matrix (e.g., Pendleton, Briggs and Meegan 1996), it has always been assumed that the source flux is unpolarized. For example, solar flare data has been used to refine the response which is used in determining the location of  $\gamma$ -ray bursts (Pendleton et al. 1992). If strong polarization effects are present in solar flares, then this will introduce erroneous corrections in BATSE's use of these flares to confirm and correct their angular dependent response matrix. Furthermore, the presence of polarization in a given burst may also affect the location results for that particular event. *The affirmation of BATSE's source location algorithm may therefore be an important by-product of our polarization studies.*

Initial comparisons between observations and simulations indicate that a number of important factors remain to be incorporated into the simulations. These include the unequal effective energy ranges amongst the LAD detectors, the precise form of the source spectrum (only power law spectra have been simulated), a more realistic spectral response (a diagonal response matrix is assumed at present), and an improved angular response. *Our proposed activities for cycle 7 include modifications to the simulations that will incorporate all of these factors.*

Studies of pulsar polarizations would be based on variations in the observed pulse profiles under different viewing geometries. Wilson et al. (1992) presented results for the Crab pulsar which are strongly suggestive of polarization effects. They presented a sequence of Crab pulse profiles collected under differing scattering geometries over the course of the 52 day orbital precession period. They found a significant change with time in the pulse profile at energies  $< 235$  keV, and little or no variation at higher energies. These results already show that a geometry dependent pulse profile exists in the BATSE data. We are proposing to take a more careful look at such data to search specifically for effects due to polarization.

### 3.0 DIRECT POLARIZATION SENSITIVITY OF BATSE

As a result of the preferred scattering angles for Compton scattering of polarized radiation, the off-axis sensitivity of thin scintillation detectors (such as the LADs) will depend, at some level, on the polarization angle of the incident flux with respect to the plane of the detector. At energies where Compton scattering dominates the interaction process, the detection sensitivity will be higher if the preferred photon scatter direction lies in the plane of the detector. For on-axis sources, the preferred scatter direction will always very nearly lie in the plane of the

Distributions such as those in Figure 1 have been used to estimate the BATSE sensitivity to burst and flare polarization. Although one might expect that the large FoV of each BATSE LAD would dilute the response to polarization effects, our simulations indicate that such effects may still be observable. In estimating the BATSE sensitivity, the response of each of the four downward-looking LADs is determined by integrating the simulated albedo flux over the full LAD ( $2\pi$ ) FoV, taking into account the angular dependence of the sensitivity. The presence of a polarization signature is tested by comparing the measured LAD counts to that expected for an unpolarized source. (In both cases, a typical level of background is added to the data.) A simple  $\chi^2$  test between the

detector. For off-axis sources, on the other hand, the sensitivity will become a function of the polarization angle of the incident flux, since some events will have a large probability of scattering completely out of the detector. We propose to investigate whether this process can provide any useful information regarding the polarization of the incident source flux, for example, by influencing the relative response of the LAD detectors to a given event. If such effects are present, they may also have a significant impact on the albedo measurements.

#### 4.0 PROPOSED ACTIVITIES FOR CYCLE 7

Our proposed plan for cycle 7 includes: 1) the reconfiguration of our simulation code to allow for more effective simulations that would also incorporate several important factors related to the LAD response (as outlined in §2); 2) perform a more detailed comparison of our simulation results for an unpolarized source with those generated by BATSE team software; 3) use the revised simulation code to refine our estimates of the BATSE polarization sensitivity over a wider range of parameter space; 4) perform a detailed analysis of events selected on the basis of geometry and total fluence; 5) explore possible means by which one could use BATSE data to investigate pulsar polarization; and 6) perform simulations to determine to what extent the array of LAD detectors may be directly sensitive to source polarization. Our efforts will concentrate on the first four of these tasks, but it can be expected that knowledge gained from this effort will be directly applicable to task 5. Archival DISCLA or CONT data will be used for the flare and burst studies. Archival on-board folded pulsar data may be used for pulsar studies.

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