Hard X-Ray Polarimetry with RHESSI

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GRB Polarization Measured by RHESSI

Astronomy

New direction for γ-rays

Eli Waxman

The origin of energetic γ-ray bursts is still unknown. But the detection of polarization of the γ-rays provides fresh insight into the mechanism driving these powerful explosions.

Gamma-ray bursts (GRBs) are short flashes of γ-rays, typically tens of seconds long[1]. First detected in the 1960s, GRBs are observed at a rate of roughly one per day. Although their sources are known to reside in distant galaxies, several billion light years away, what these sources are remains a mystery. But a new clue is provided by Wayne Coburn and Steven Boggs[2], who, on page 415 of this issue, report the detection of polarization — a particular orientation of the electric-field vector — in γ-rays from a burst. This discovery may shed light on the identity of the sources of GRBs, as well as on the mechanism by which the γ-rays are produced.

The huge energy release associated with a GRB is thought to be created by the gravitational collapse of a star to form a black hole or neutron star[3]. The contraction causes gravitational energy to be released. The typical energy output of a GRB corresponds to the conversion of about 1% of the Sun's mass into energy: in comparison, the energy output of an atom bomb is equivalent to the conversion to energy of about 1 gram of matter.

The energy released in the collapse seems to be carried away from the source in the form of a highly relativistic jet (Fig. 1), in which particles move at nearly the speed of light. As the jet reaches a radius of about 100 million kilometres from its source, part of this energy is converted to γ-rays, which become the GRB. At a later stage still, as the jet expands to a scale of 10 billion kilometres, an 'afterglow'

The detected polarization signal is, then, an average over the polarization of radiation produced at different points within the source. If the direction of polarization varies randomly from place to place in the jet, then the observed polarization signal is likely to average out to zero. But this 'washing out' of the polarization signal will not happen if the polarization direction is the same everywhere. For polarization produced by the synchrotron mechanism, this means that the γ-ray-producing region is suffused by an ordered magnetic field, oriented in the same direction everywhere (Fig. 2a).

The direction of polarization reported by Coburn and Boggs[2] remained constant throughout the duration of the GRB, but the γ-ray flux varied significantly. So it seems unlikely that such a strong, constant, ordered field could be generated in the region where the γ-rays are produced. Rather, this suggests that the strong field originates near the collapsing object, and is then carried by (or perhaps even drives) the jet outwards from the source: the mechanism by which gravitational energy is extracted and powers the jet is, possibly, electromagnetic.

But there could be another explanation.

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Why is Polarimetry Important?

Four measurable quantities of EM radiation:

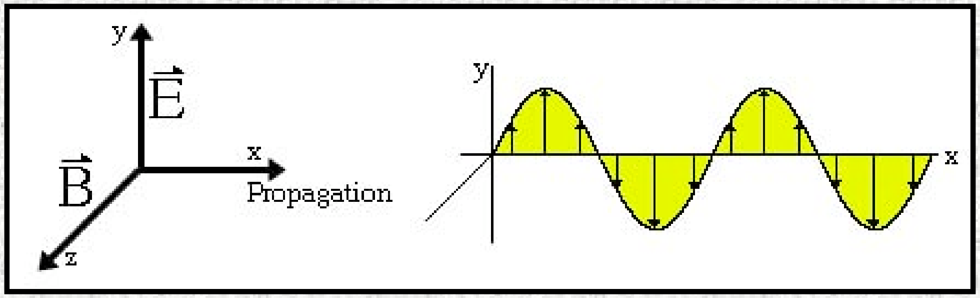
1. **direction** (where is it coming from?)
2. **intensity** (how bright is it?)
3. **energy** (what is it's spectrum?)
4. **polarization** (geometry, radiation mechanism)

Polarization arises as the consequence of some type of asymmetry, either in the source region or in the intervening medium.

To some extent polarization can also provide clues about the radiation mechanism.

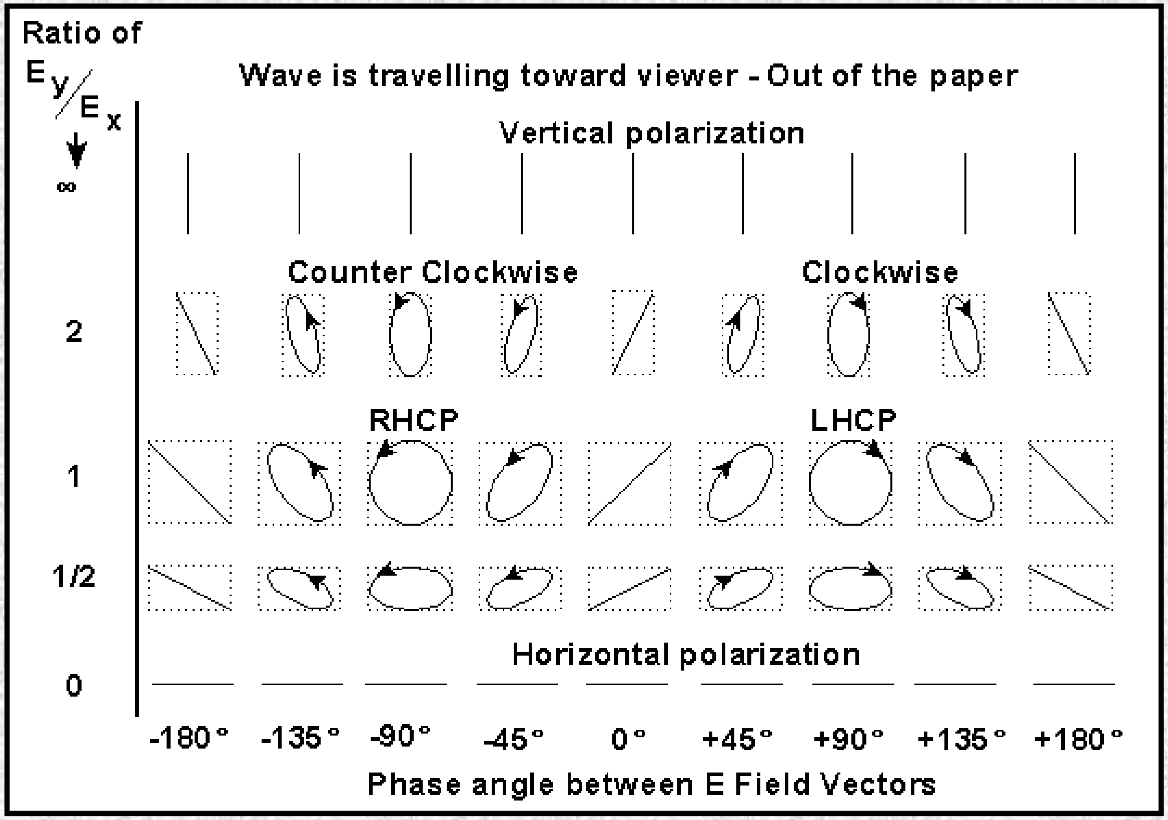
What is Polarization?

Electromagnetic radiation can be represented as a transverse wave made up of mutually perpendicular, fluctuating electric and magnetic fields.



The polarization of an EM wave refers to the orientation of its associated electric field vector.

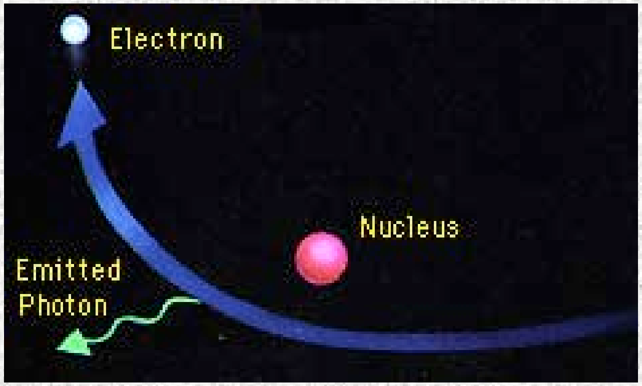
The Zoo of Polarization States



In what follows we will concentrate exclusively on linear polarization (at energies above 20 keV).

Bremsstrahlung Radiation

The radiation associated with the acceleration of a charged particle in the electrostatic field of an ion.



Photons tend to be emitted perpendicular to electron's plane of motion.

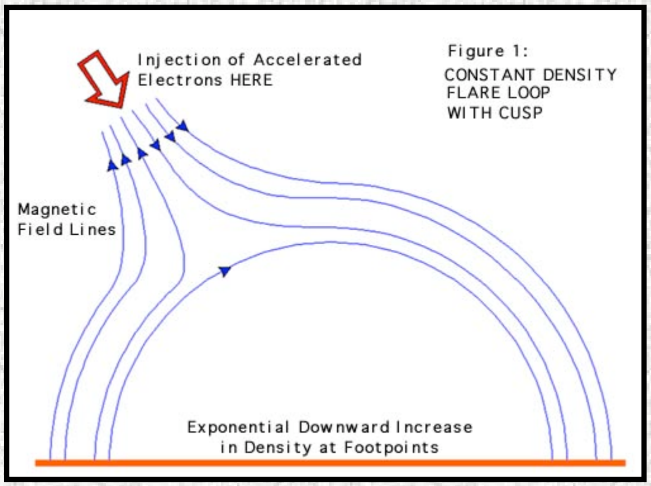
The polarization vector tends to be parallel to the direction of acceleration.

Degree of linear polarization can reach 80%.

Polarization in Solar Flares

The hard X-ray continuum is dominated by electron bremsstrahlung emission.

Observations may be most effective at higher energies (> 100 keV), above thermal emission.



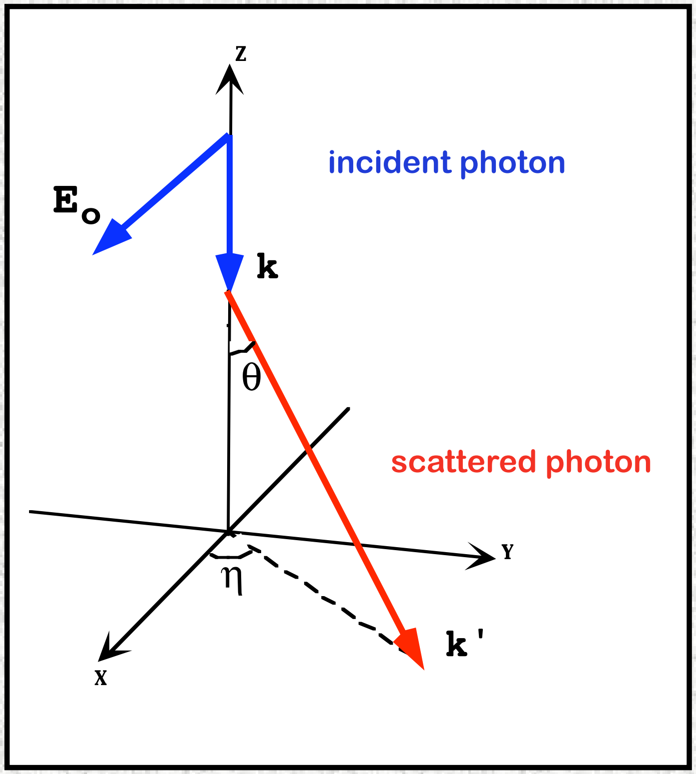
Model parameters include :

1) pitch angle distribution
2) geometry of the B-field
3) viewing angle
4) atmospheric density profile

Models predict polarization levels as high as 20 or 30%.

Basic Principles of Compton Polarimetry

10 keV – 30 MeV



Polarimetry relies on the fact that…

photons tend to Compton scatter at right angles to the incident polarization vector

$$d\sigma = \frac{r_o^2}{2}\, d\Omega \left(\frac{E'}{E_o}\right)^2 \left(\frac{E_o}{E'} + \frac{E'}{E_o} - 2\sin^2\theta\cos^2\eta\right)$$

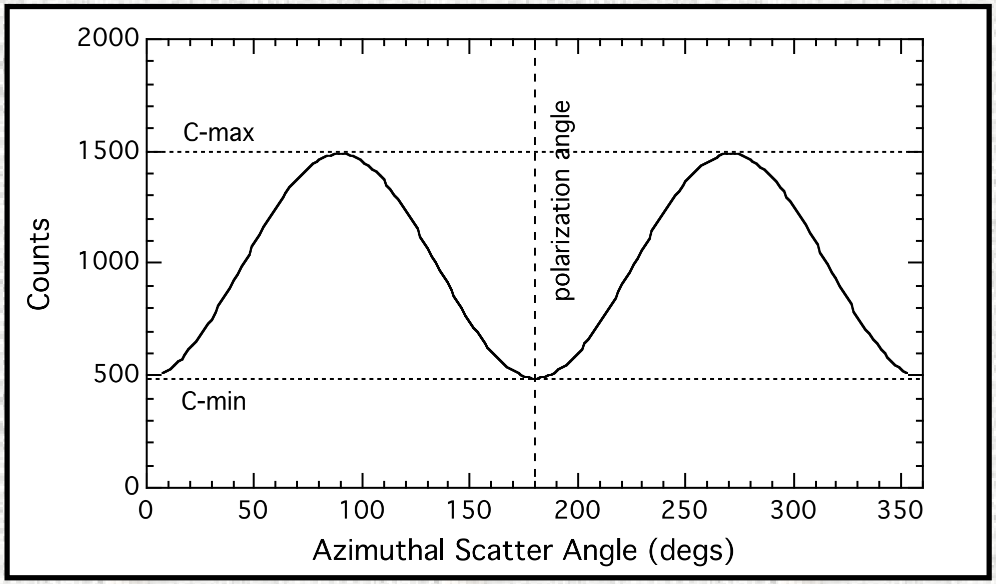
$$E' = \frac{E_o}{1 + \frac{E_o}{mc^2}(1-\cos\theta)}$$

θ is the Compton Scatter Angle

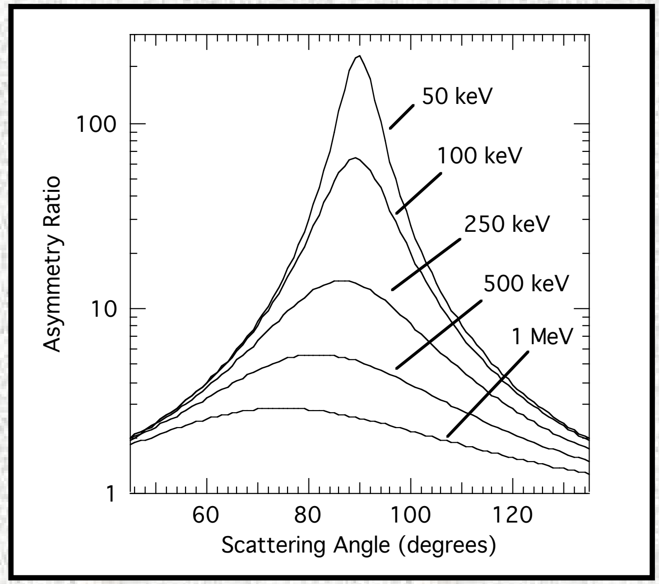
η is the Azimuthal Scatter Angle

The Polarization Signature

For a fixed Compton scatter angle (θ), the azimuthal distribution of scattered photons contains the polarization signature.



$$C(\eta) = A\cos 2(\eta - \varphi) + B$$



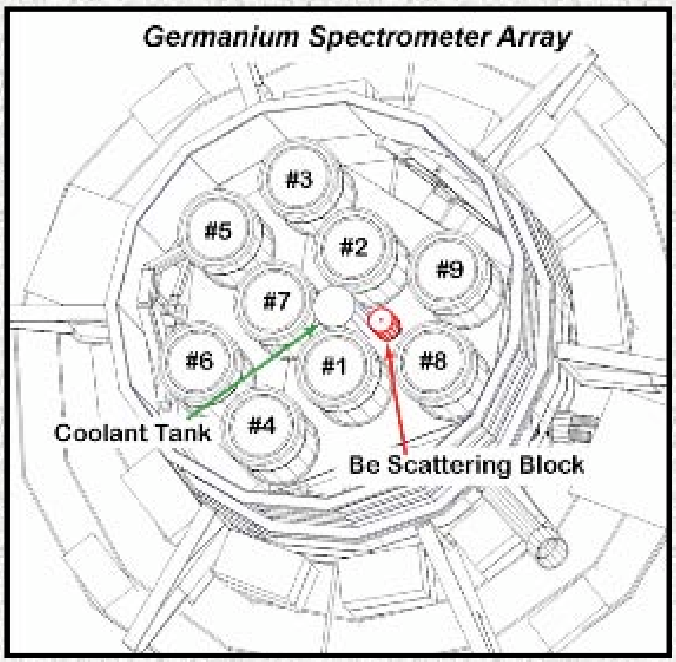
Asymmetry Ratio

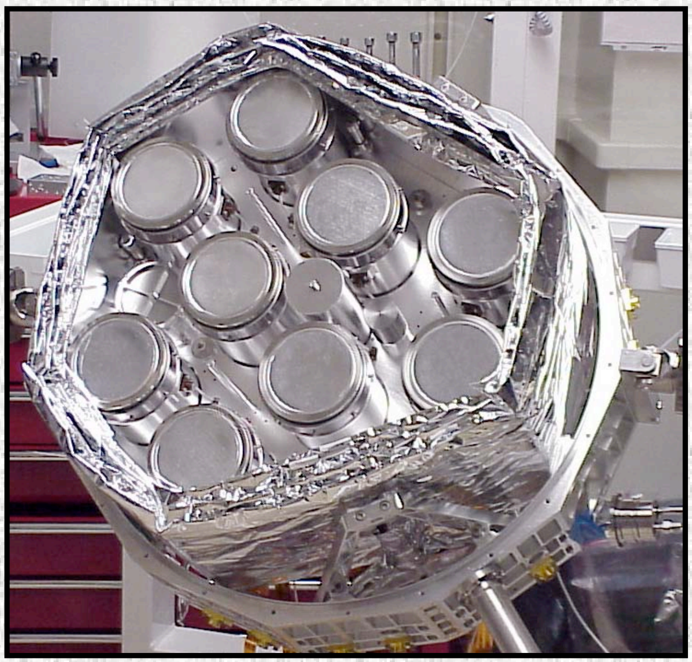
The amplitude of the modulation defines the level of polarization.

The minimum of the distribution defines the plane of polarization.

RHESSI as a Polarimeter

Two modes :
Low-Energy Mode (Be-Ge, 20-100 keV)
High-Energy Mode (Ge-Ge, >200 keV)





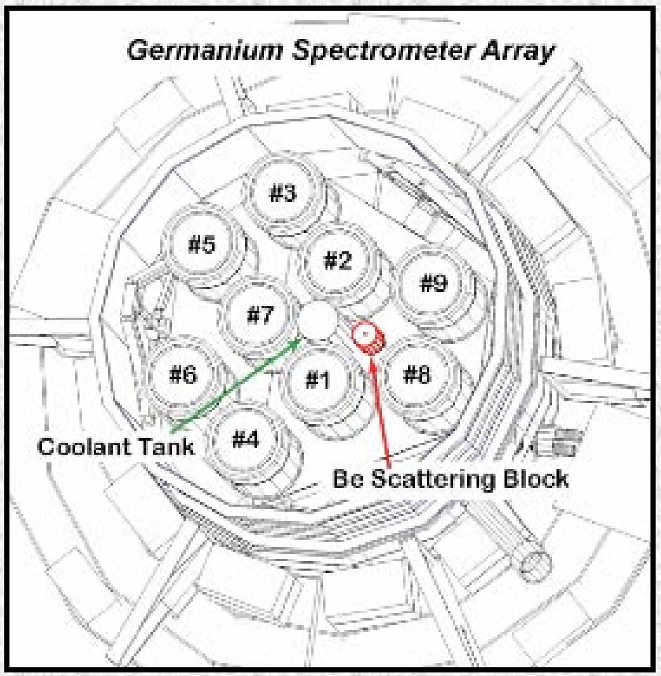
Spacecraft rotation facilitates polarization measurements.

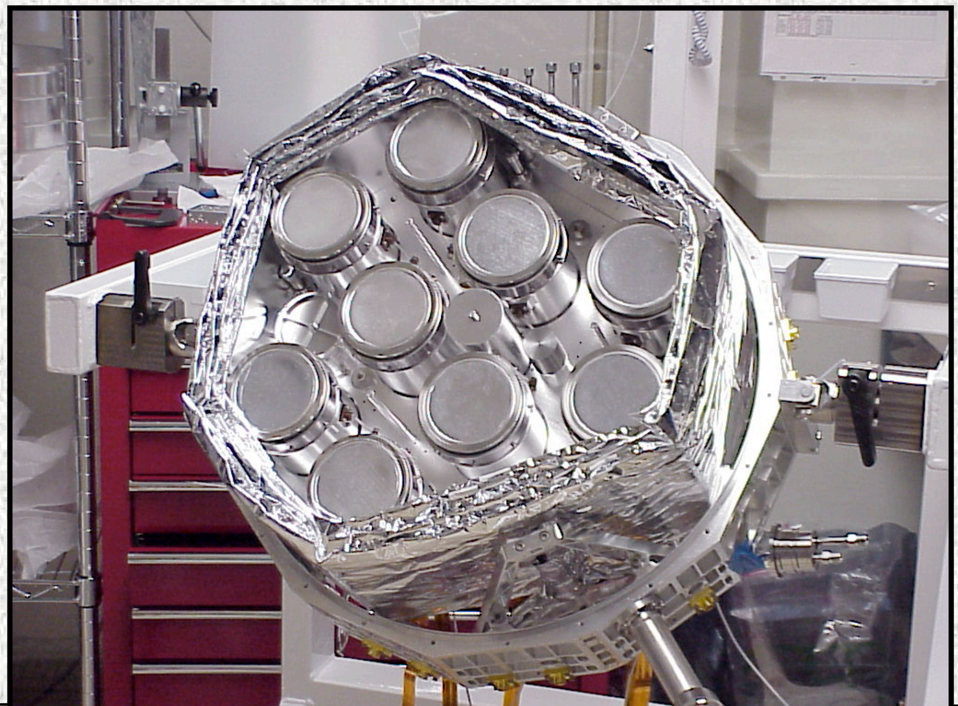
RHESSI as a Polarimeter (20-100 keV)

A small (3 cm diam by 3.5 cm high) cylinder of Be serves as a Compton scattering element that scatters photons into the rear segments of the adjacent Ge detectors.

The Ge detectors measure the distribution of the scattered radiation.

Spacecraft rotation provides for fine sampling of scatter distribution.



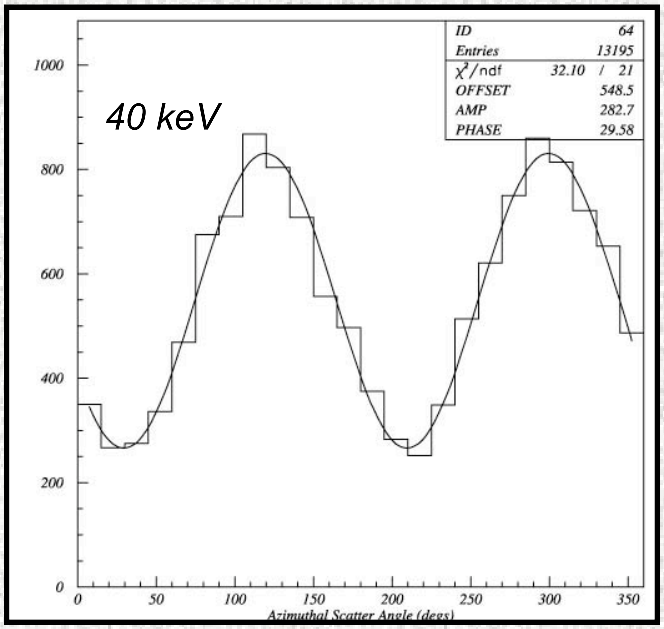


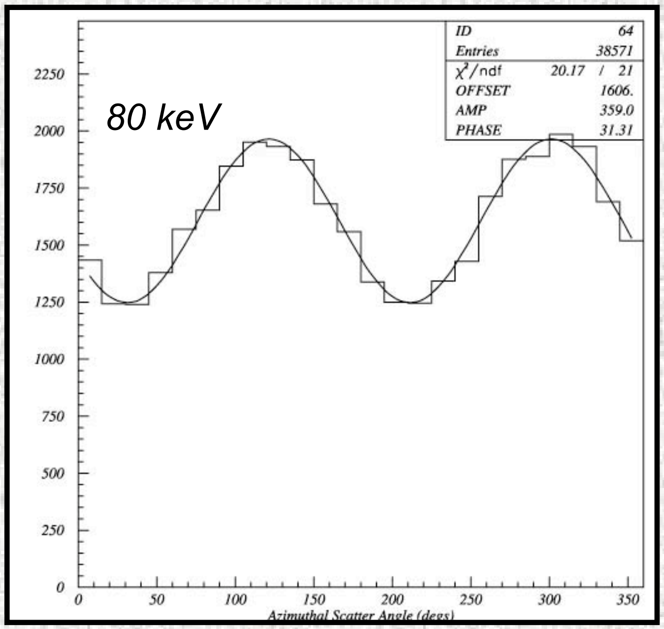
The Polarization Signal - Simulation Results

We have used a modified version of GEANT3 to carry out Monte Carlo simulations of the polarimetric capabilities of RHESSI.

A valid polarimeter event is one which produces a measurable energy deposit in the rear segment of Ge detectors 1, 8, or 9.

Detector 2 is not currently operating as a segmented detector.



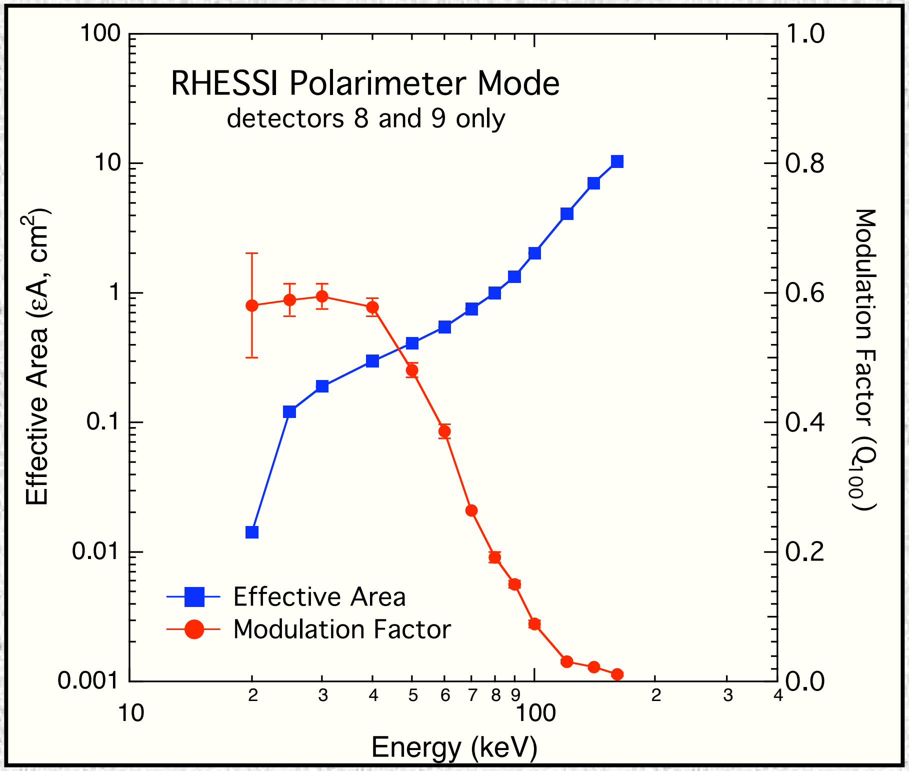


RHESSI Low-Energy Polarimetry

Be-Ge Scatter Events, 20-100 keV

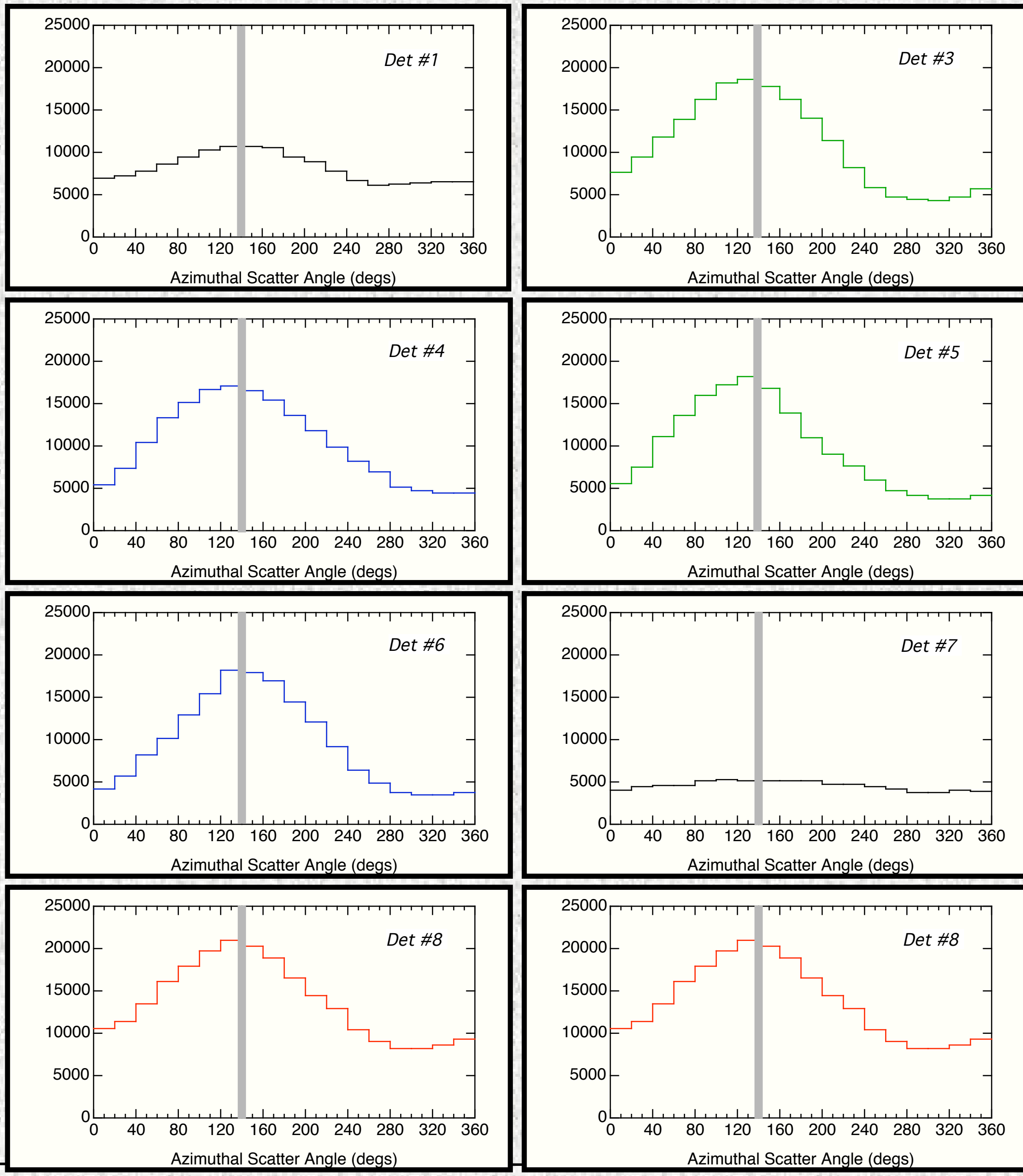
Relies on front/rear Ge segmentation. Low energy solar photons (<100 keV) can reach rear segments only by scattering in the Be.

FoV is limited by the collimation of Be block (~1°).



McConnell et al., Solar Physics, 210, 125 (2002)

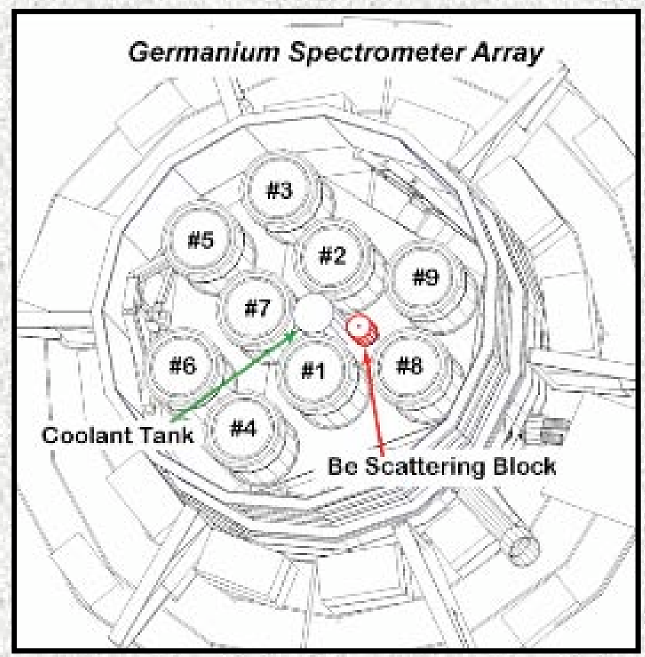
Nature of the RHESSI Data



X4.8 Flare - 23 July 2002

00:26 – 00:42 UT

Rear Segment Data
(20 – 40 keV)
dominated by spin modulation of atmospheric background and albedo

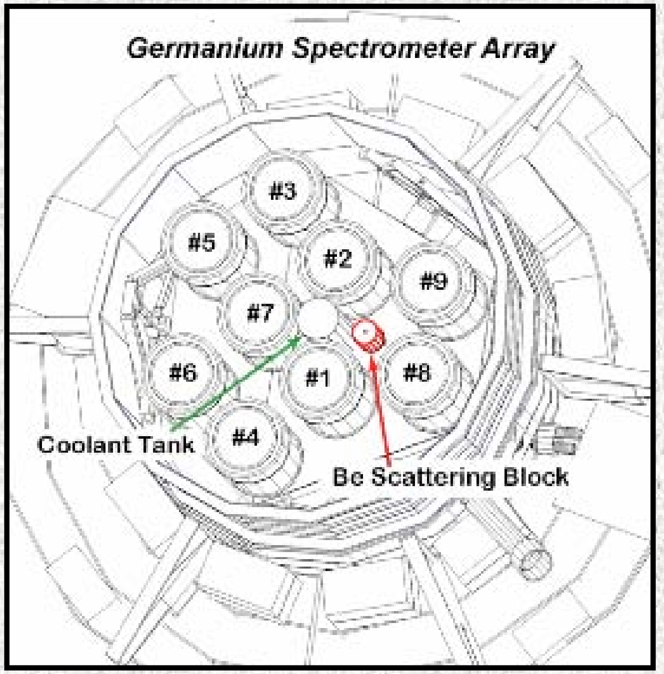


An Initial Approach to RHESSI Data Analysis

Three pairs of detectors with similar background :

detectors 8/9, detectors 3/5 and detectors 4/6.

The data from detectors 3-6 can be used as background estimate for the polarimeter mode detectors 8/9.

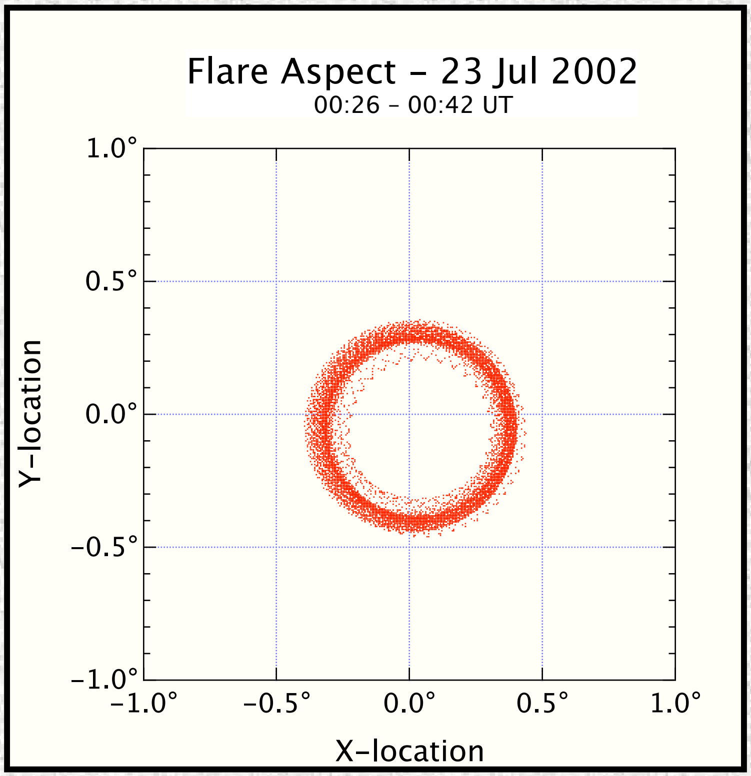


***Limitations* :**

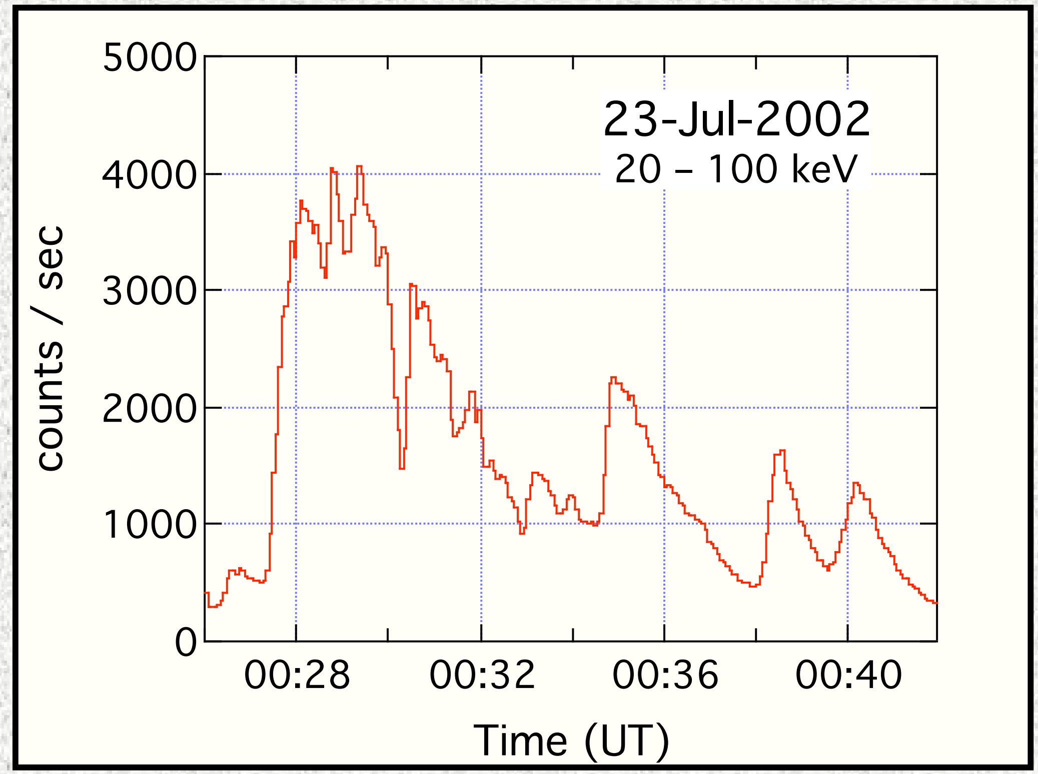
- **Does not use detector #1**
- **Assumes symmetric geometry**
- **No modeling of Earth albedo**
- **Need relative count rate corrections**

X4.8 Flare of 23-July-2002

Flare location : S13E72



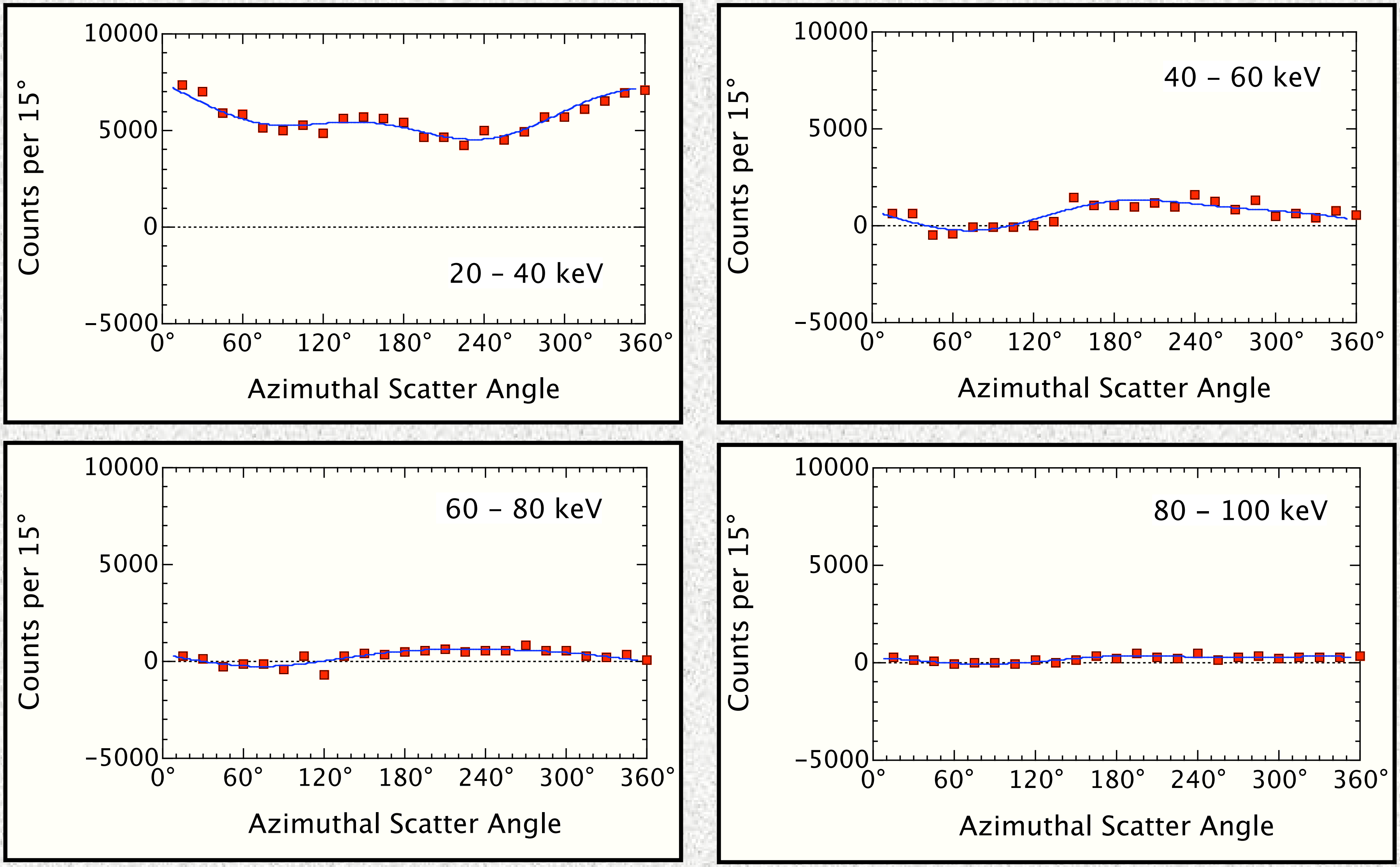
location vs. time within FoV



rear segment count rate

“Background”-Subtracted Data vs. Energy

X4.8 Flare, 23 July 2002, 00:26 - 00:42 UT



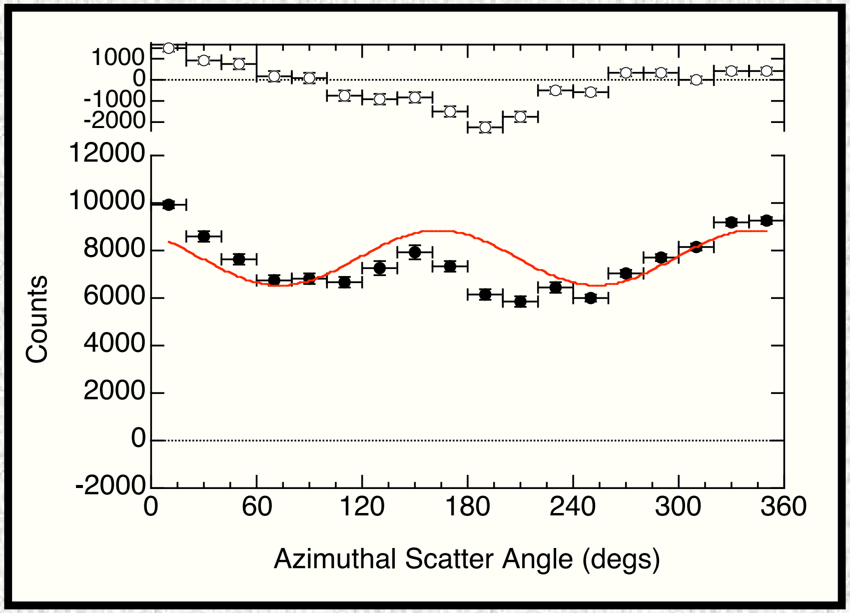
Polarization Analysis

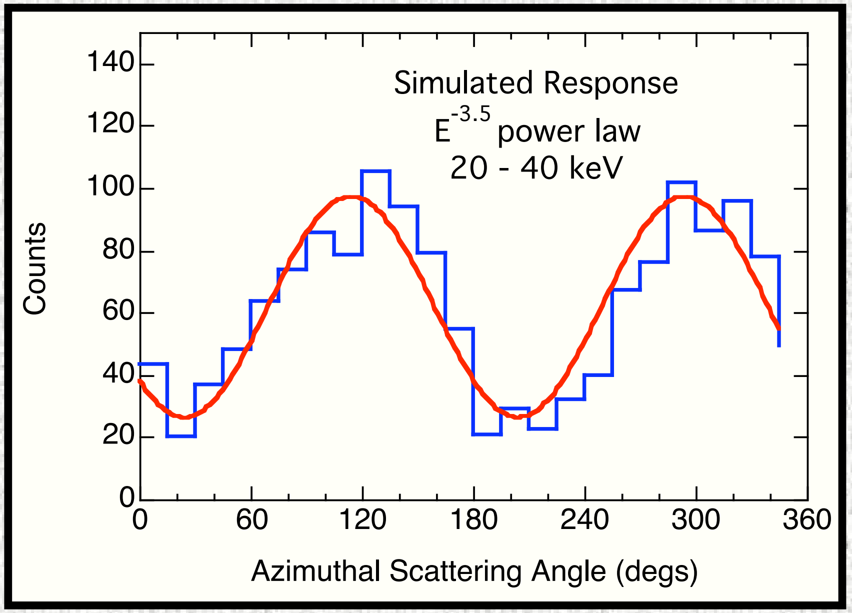
Two Component Analysis

$$f(\eta) = \underbrace{A + B\sin 2(\eta - \varphi)}_{\text{Polarization signal}} + \underbrace{C\sin\alpha(\eta - \psi)}_{\text{Systematic Component}}$$

1. Systematic Component:
  - Single sinusoid component.
  - Dominates the response at high energies.
  - Appears to be due to vignetting of the source by spacecraft rotation (collimation effects).
  - This component averages to zero.
2. Polarization Signal
  - Double sinusoid component.

20 - 40 keV Analysis





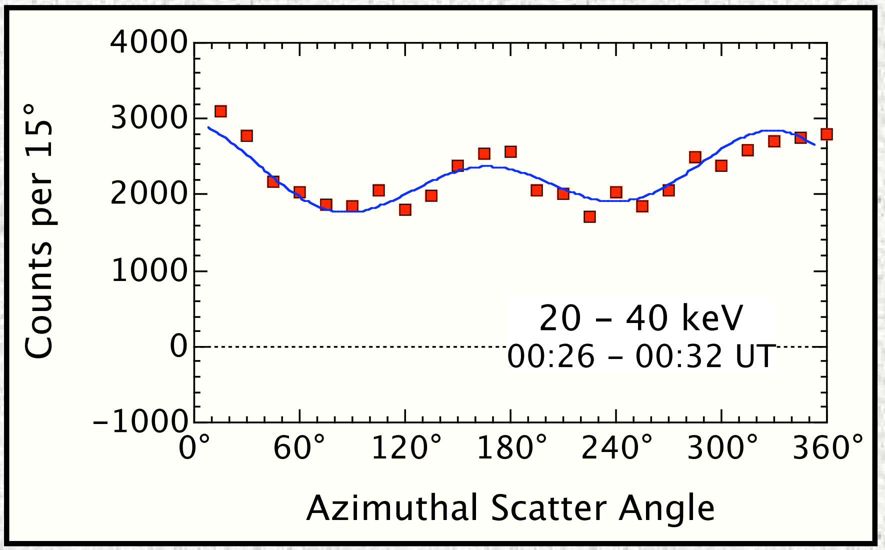
$Q_{data} = 0.15$ $Q_{100} = 0.57$

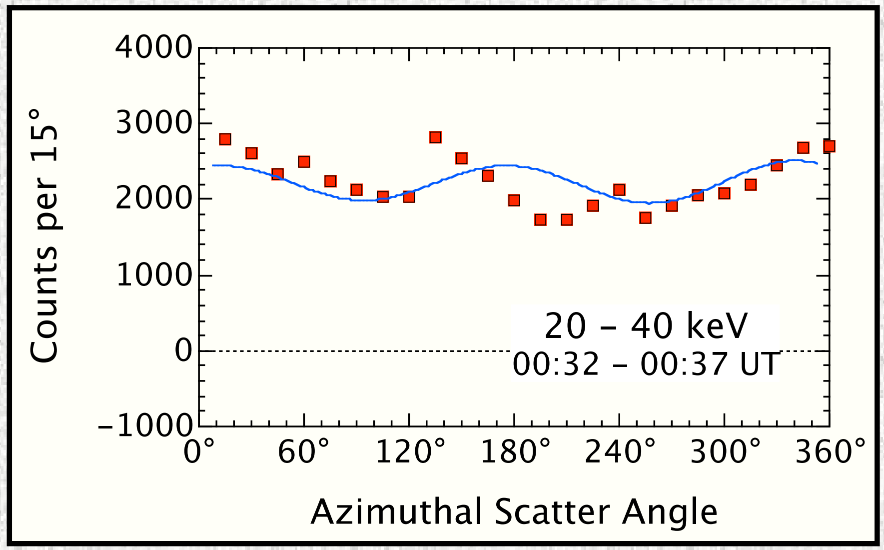
$\pi = Q_{data} / Q_{100} = 0.26$

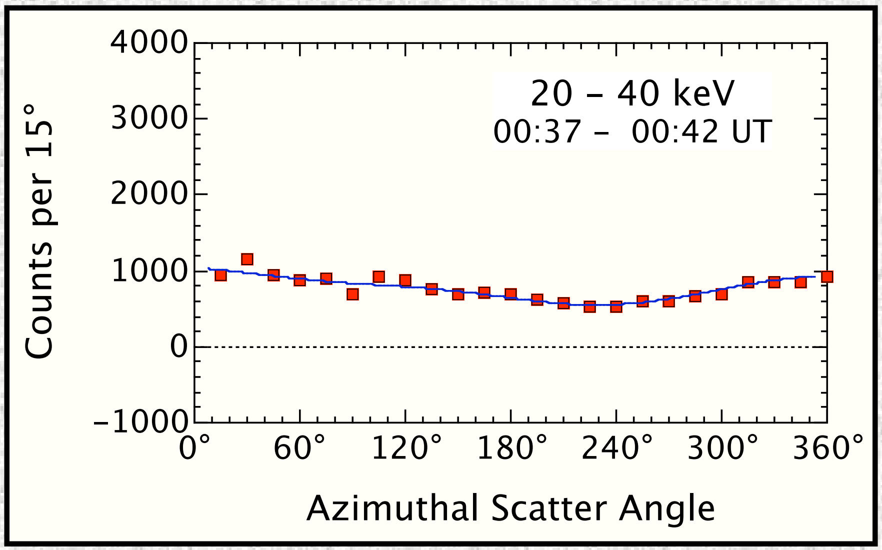
Estimated Polarization ≈ 26%

"Background"-Subtracted Data vs. Time

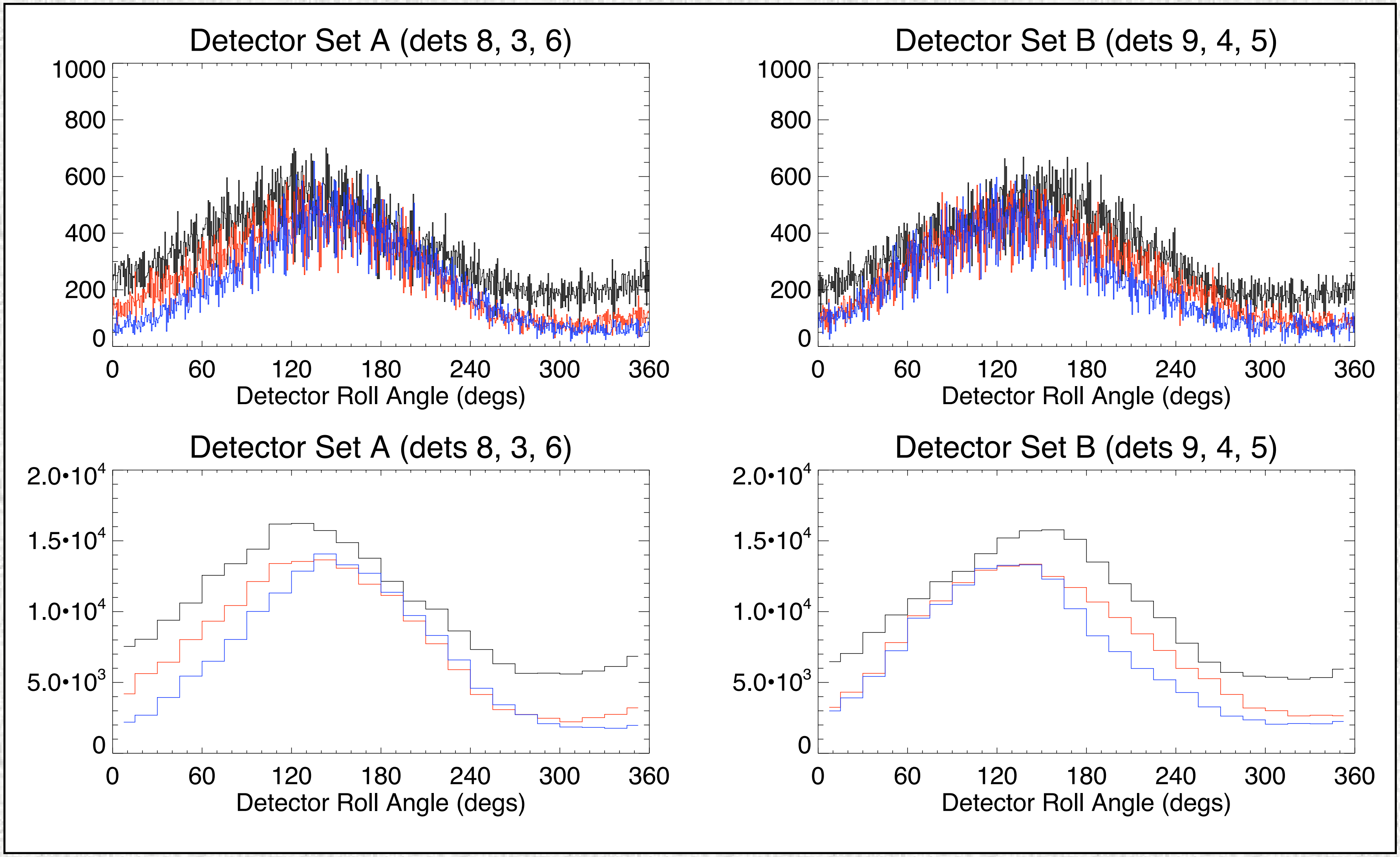
X4.8 Flare, 23 July 2002, 20 - 40 keV



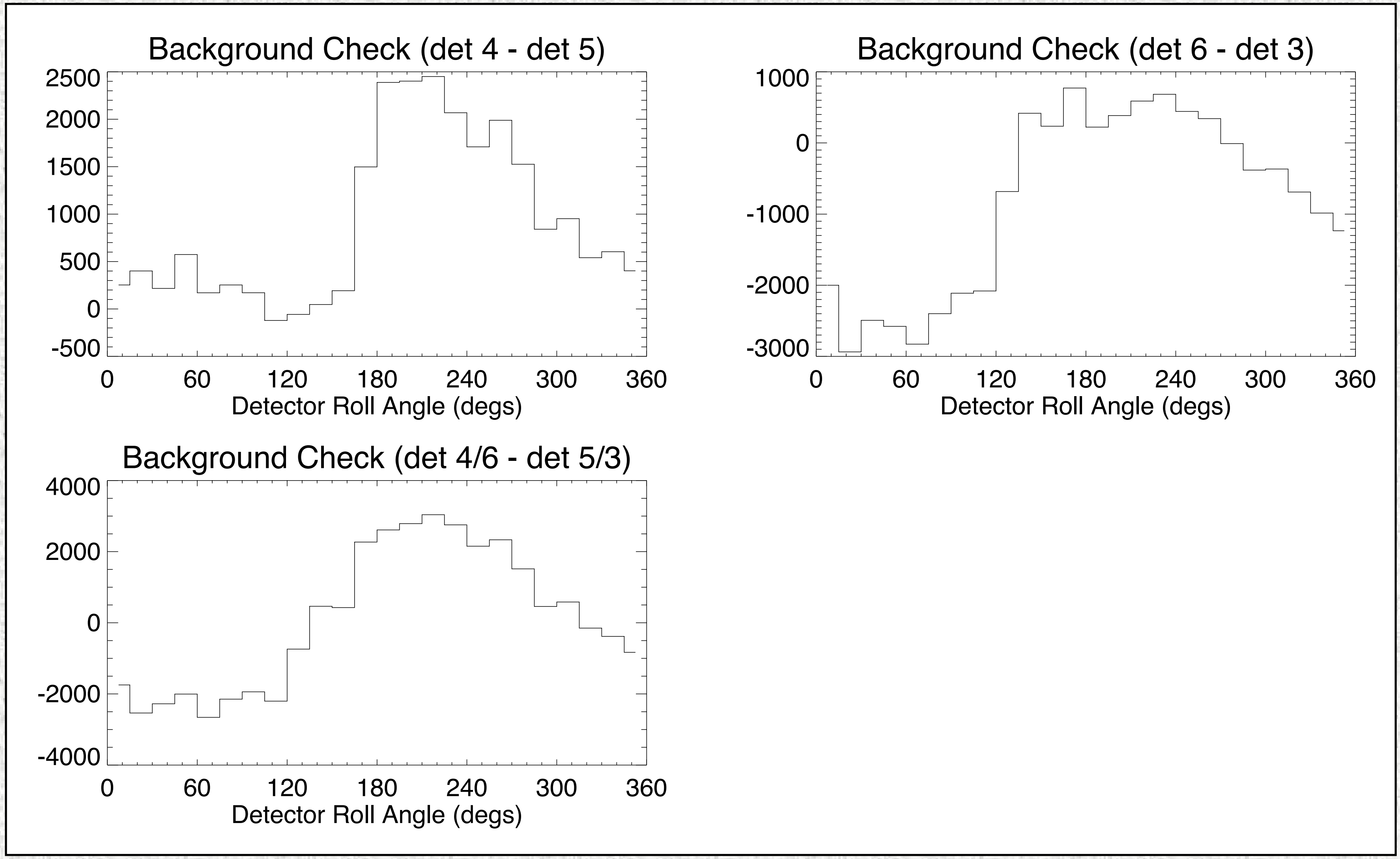




Systematic Issues

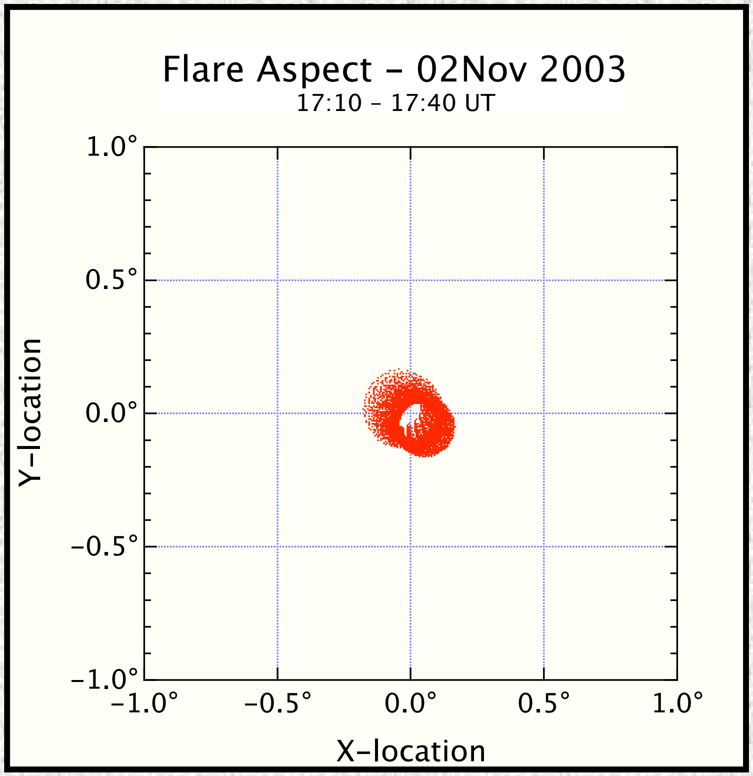


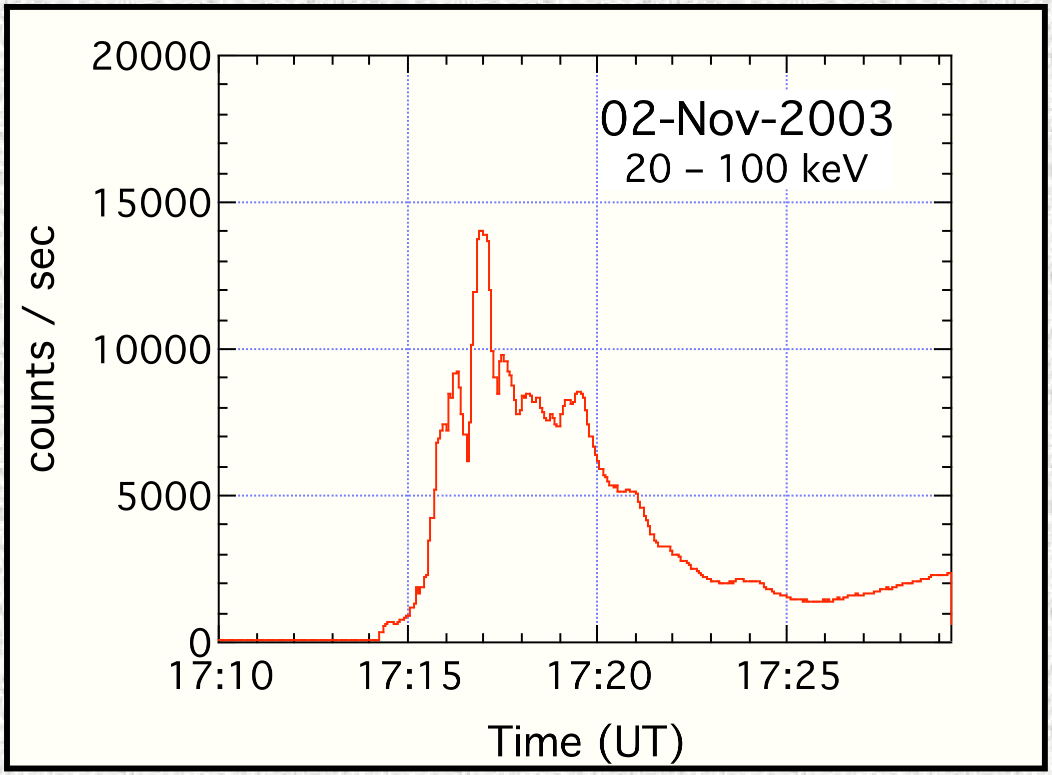
Systematic Issues



X8.3 Flare of 02-Nov-2003

Flare location : S14W56



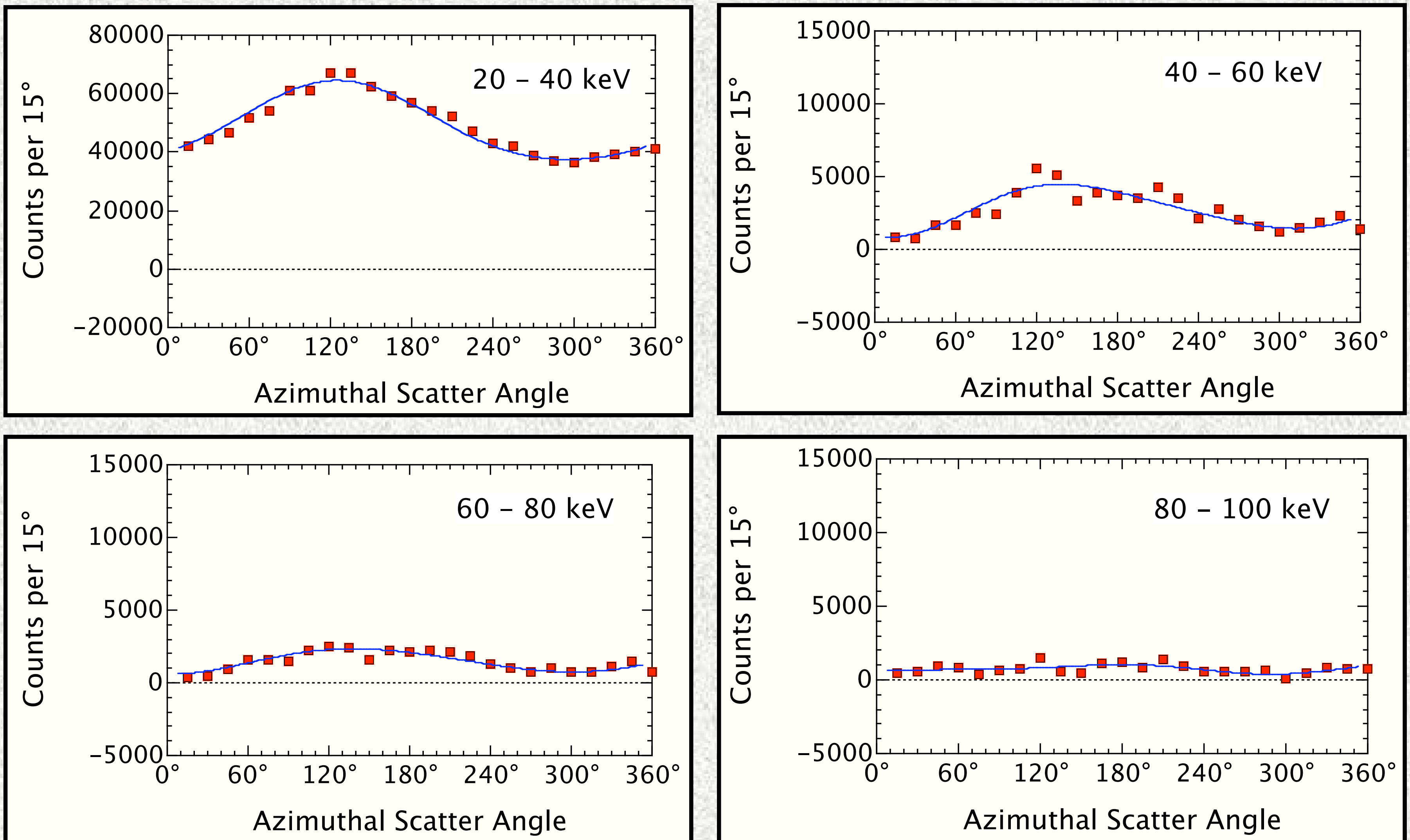


location vs. time within FoV

rear segment count rate

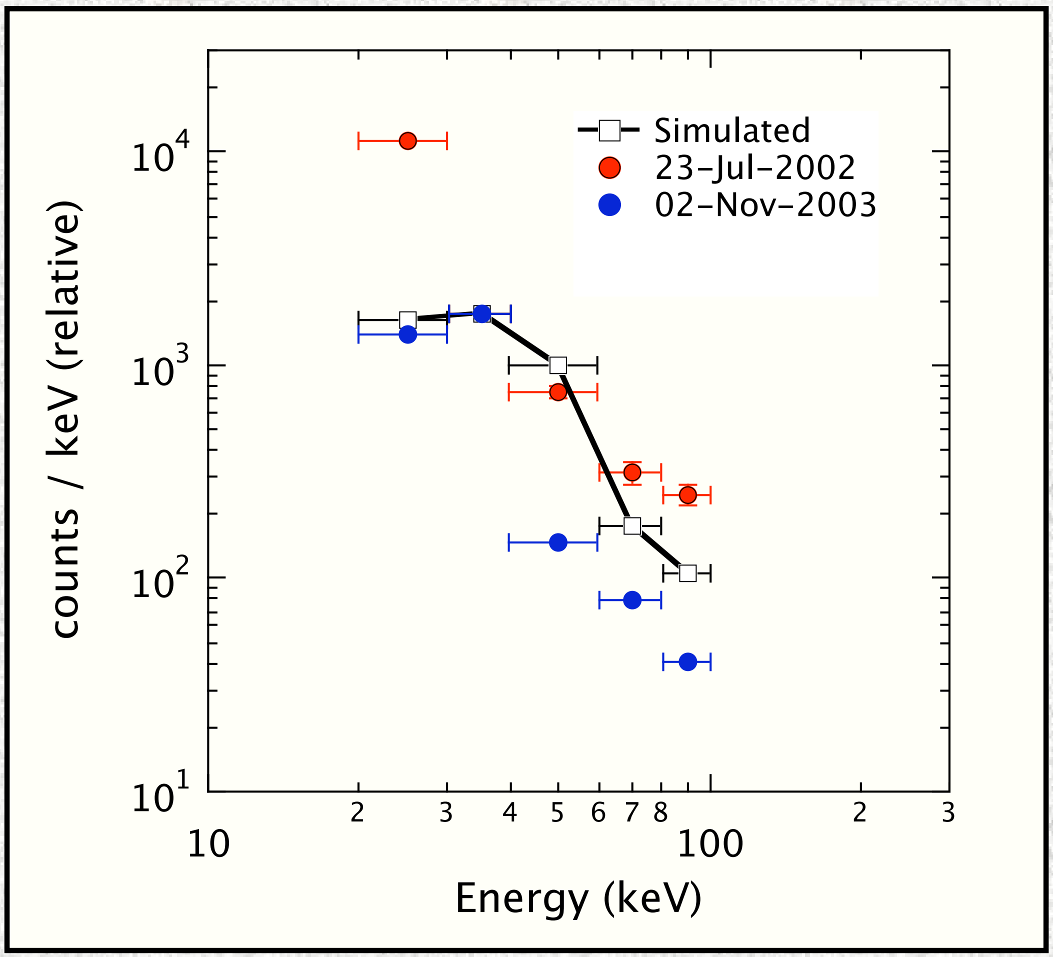
“Background” Subtracted Data

X8.3 Flare, 02 Nov 2003, 17:10 - 17:40 UT



Be-Scattered Flux Spectrum

Flare data compared with simulated data.



all spectra normalized at 35 keV

The data show a generally decreasing count rate versus energy.

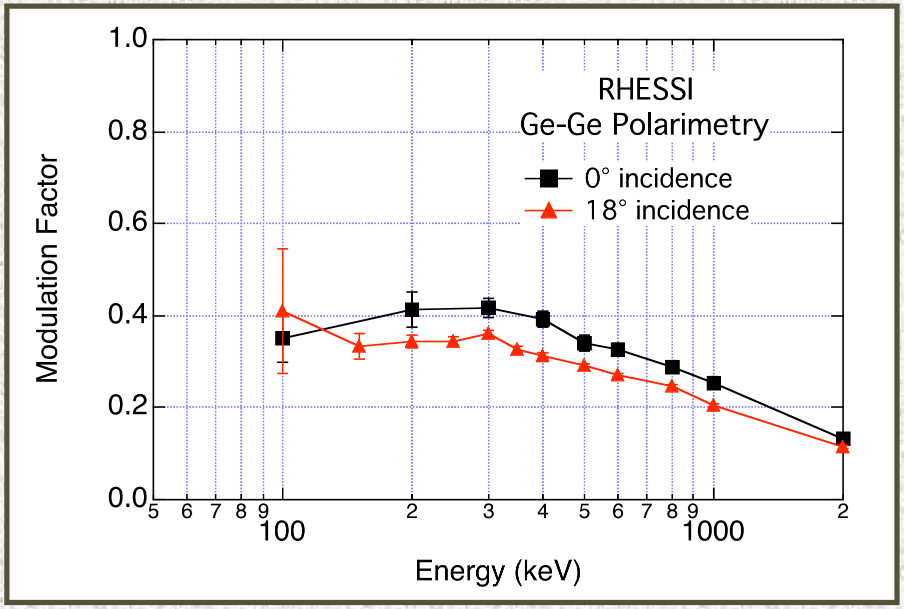
The simulated spectrum is based on an incident $E^{-3.5}$ photon spectrum.

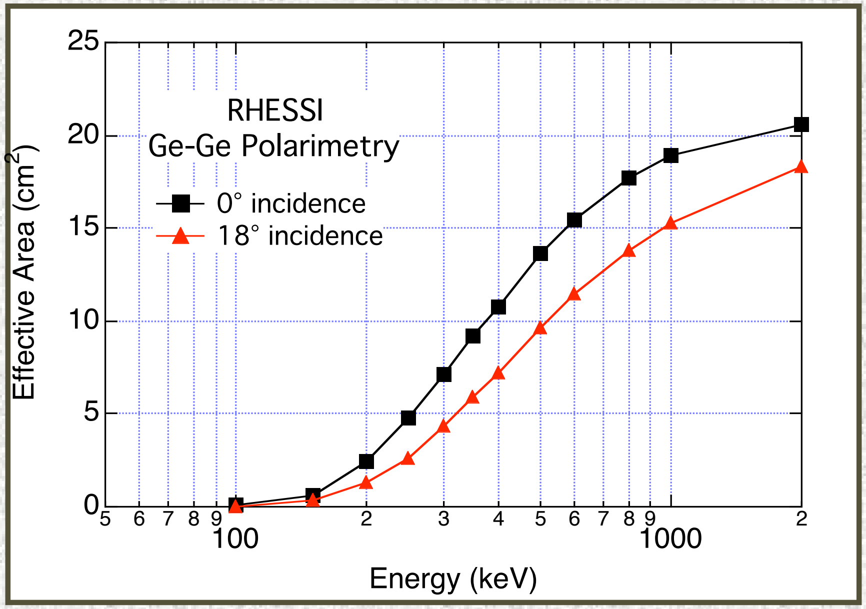
Comparison with simulations show some discrepancies.

RHESSI High-Energy Polarimetry

BGe-Ge Scatter Events, > 250 keV

Lack of detector shielding provides a large FoV (~4π).
The FoV contains significant non-uniform mass distributions.





A Surprising Announcement

letters to nature

Polarization of the prompt γ-ray emission from the γ-ray burst of 6 December 2002

Wayne Coburn* **& Steven E. Boggs*†**

* *Space Sciences Laboratory, and † Department of Physics, University of California, Berkeley, California 94720, USA*

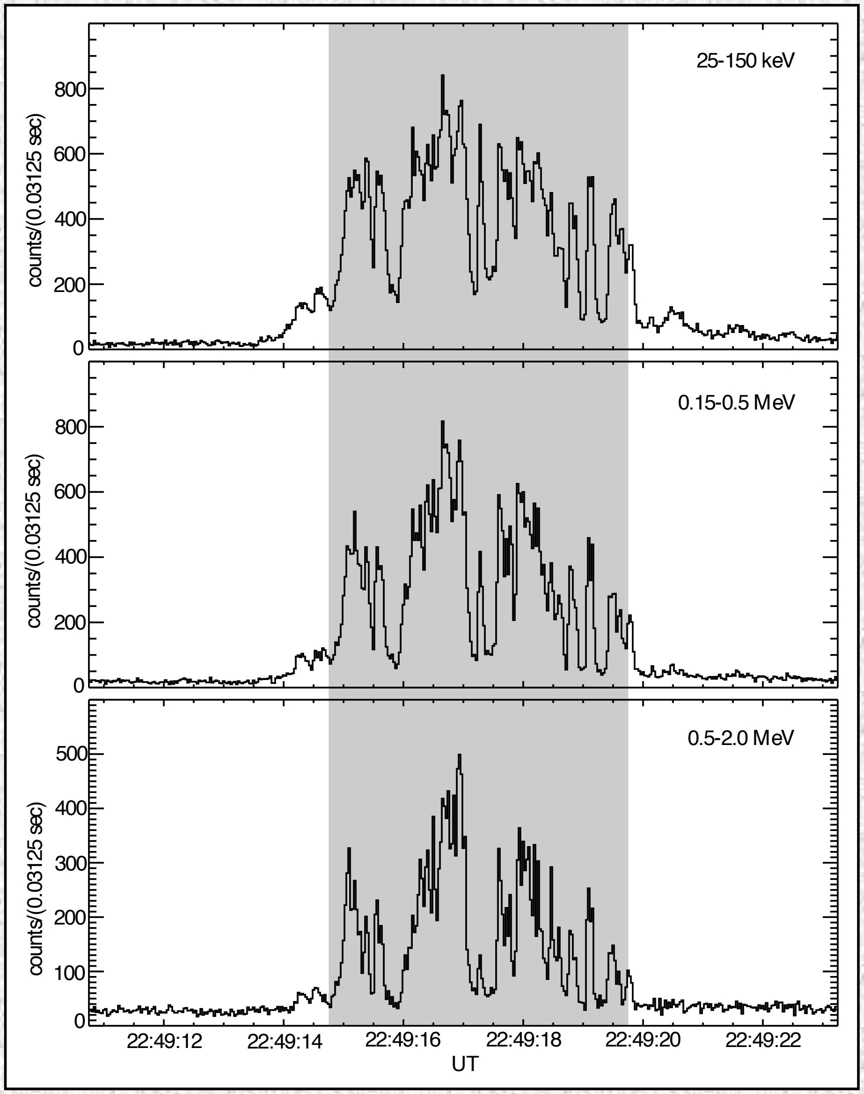
Observations of the afterglows of γ-ray bursts (GRBs) have revealed that they lie at cosmological distances, and so correspond to the release of an enormous amount of energy[1,2]. The nature of the central engine that powers these events and the prompt γ-ray emission mechanism itself remain enigmatic because, once a relativistic fireball is created, the physics of the afterglow is insensitive to the nature of the progenitor. Here we report the discovery of linear polarization in the prompt γ-ray emission from GRB021206, which indicates that it is synchrotron emission from relativistic electrons in a strong magnetic field. The polarization is at the theoretical maximum, which requires a uniform, large-scale magnetic field over the γ-ray emission region. A large-scale magnetic field constrains possible progenitors to those either having or producing organized fields. We suggest that the large magnetic energy densities in the progenitor environment (comparable to the kinetic energy densities of the fireball), combined with the large-scale structure of the field, indicate that magnetic fields drive the GRB explosion.

is the azimuthal scatter angle, η is the direction of the polarization vector, and $\mu_{\rm m}$ is the average value of the polarimetric modulation factor for the instrument. Although RHESSI has a small effective area ($\sim$20 cm^2) for events that scatter between detectors, it has a relatively large modulation factor in the 0.15–2.0 MeV range, $\mu_{\rm m} \approx 0.2$, as determined by Monte Carlo simulations described below.

In comparison with other γ-ray instruments (COMPTEL, BATSE) that have attempted to measure polarization in the past[5,6], RHESSI has the major advantage of quickly rotating around its focal axis (centred on the Sun) with a 4-s period. Rotation averages out the effects of asymmetries in the detectors and passive materials that could be mistaken for a modulation. Because polarimetric modulations repeat every 180°, any source lasting more than half a rotation (2 s) will be relatively insensitive to the systematic uncertainties that typically plague polarization measurements. Finally, although the RHESSI detectors have no positioning information themselves, they are relatively loosely grouped on the spacecraft, allowing the azimuthal angle for a given scatter to be determined to within $\Delta\phi = 13°$ r.m.s. This angular uncertainty will decrease potential modulations by a factor of 0.95, which is included in our calculated modulation factor.

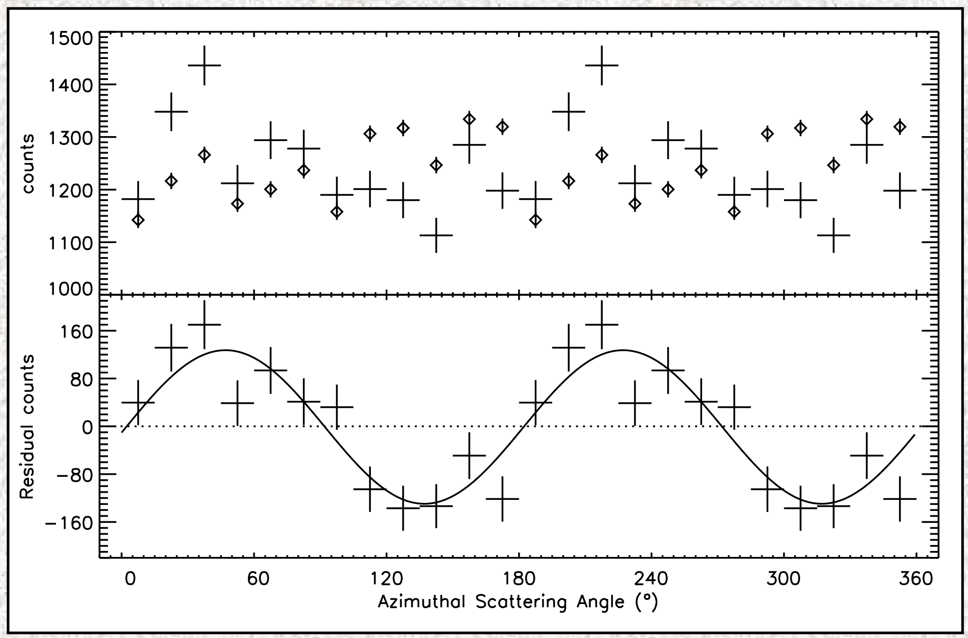
Prompt γ-ray emission from GRB021206 was detected with RHESSI on 6 December 2002 at 22:49 UT (Fig. 1). This GRB was also observed[7] with the Interplanetary Network (IPN), which reported a 25–100 keV fluence of 1.6×10^{-4} erg cm^{-2}, and a peak flux of 2.9×10^{-5} erg cm^{-2} s^{-1}, making this an extremely bright GRB. The IPN localized[8] GRB021206 to a 57 square-arcminute

The Data for GRB 021206



Fairly strong, short burst.

18° off-axis – minimal attenuation



Coburn & Boggs, Nature, 22 May 2003, 423, 415