Hard X-Ray Solar Flare Polarimetry with RHESSI

Mark L. McConnell¹, David M. Smith², A. Gordon Emslie³, Gordon J. Hurford², Robert P. Lin², and James M. Ryan¹

¹Space Science Center, University of New Hampshire, Durham, NH
²Space Sciences Laboratory, U.C. Berkeley, Berkeley, CA
³Physics Department, University of Alabama, Huntsville, AL
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.

Measurements of hard X-ray polarization can shed light on the geometry of the acceleration process.

Model parameters include:

1) pitch angle distribution
2) B-field geometry
3) viewing angle
4) atm density profile

Models predict polarization levels as high as 20 or 30%.
Predictions for Solar Flare Polarization

Single vertical (radial) flux tube

Integrated over a loop

Langer and Petrosian (1977)

Leach and Petrosian (1983)
Polarimetry relies on the fact that…

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

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

\[ C(q) = A \cos 2\theta + B \]

The amplitude of the modulation defines the level of polarization.

The scattering angle corresponding to the minimum of the distribution defines the plane of polarization.
Modulation Factor

Modulation Factor for a 100% polarized beam represents a figure-of-merit for the polarimeter:

\[ Q = \frac{C_{\text{max}} - C_{\text{min}}}{C_{\text{max}} + C_{\text{min}}} = \frac{A}{B} \]

\[ C(\ ) = A \cos 2(\ ) + B \]
Minimum Detectable Polarization (MDP)

\[
MDP = \frac{n}{Q_{100}} S \sqrt{\frac{2(S+B)}{T}}
\]

S = source counting rate
B = background counting rate
T = observation time
\(Q_{100}\) = modulation factor for 100% polarization

Sensitivity can be improved by:
1) Increasing S (efficiency or geometric area)
2) Decreasing B
3) Increasing T
4) Increasing \(Q_{100}\) (optimizing geometry)
RHESSI as a Polarimeter (20 – 100 keV)

A small (3 cm diam by 3.5 cm high) cylinder of Be serves as scattering element.

The Ge detectors measure the distribution of the scattered radiation.

The rotation of the spacecraft rotation provides an effective method for fine sampling of the scatter distribution.
Segmented Ge detectors

The segmented nature of the Ge detectors means that low energy photons can reach the rear Ge segments only by scattering off other material.

Mechanical configuration of a Ge detector.  
Field geometry of a Ge detector.
Monte Carlo Simulations

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.

We have simulated a very narrow beam (just covering the front surface area of the Be) to study the intrinsic polarimetry parameters of RHESSI.

A broader beam (covering the full front surface of the telescope tube) has been used to study the effects of scattering into the rear Ge segments.
The Polarization Signal - Simulated Results

Top row shows results for narrow incident beam (no spacecraft scattering).

Bottom row shows results for wide incident beam (with spacecraft scattering).

Note the significant degradation of signal at 80 keV.
The effective area is defined for both a narrow beam and a broad beam.

The broad beam simulation incorporates the effects of scattering of solar flux into the rear Ge segments, which leads to an increase in effective area at higher energies.
The modulation factor is a measure of the quality of the polarization signal.

Scattering of incident solar flux reduces the quality of the polarization signal. (The scattered flux is not modulated.)
The figure-of-merit is a measure of the intrinsic capability to measure polarization.

Here, it is defined as the product of (effective area)$^{1/2}$ and the modulation factor.

As defined here, it does not incorporate the effects of detector background.
Sample background spectra for rear segments.

Data are shown here for the three detectors that are used in polarization studies.
### HESSI Sensitivity to Solar Flare Polarization

**Minimum Detectable Polarization (MDP)**

<table>
<thead>
<tr>
<th>Event Duration</th>
<th>20 sec</th>
<th>100 sec</th>
<th>200 sec</th>
<th>500 sec</th>
<th>1000 sec</th>
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<tbody>
<tr>
<td><strong>X2 class flare</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 – 40 keV</td>
<td>11%</td>
<td>5%</td>
<td>3%</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>40 – 60 keV</td>
<td>53%</td>
<td>24%</td>
<td>17%</td>
<td>11%</td>
<td>8%</td>
</tr>
<tr>
<td>60 – 80 keV</td>
<td>–</td>
<td>–</td>
<td>73%</td>
<td>46%</td>
<td>33%</td>
</tr>
<tr>
<td><strong>X10 class flare</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 – 40 keV</td>
<td>5%</td>
<td>2%</td>
<td>1%</td>
<td>1%</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>40 – 60 keV</td>
<td>17%</td>
<td>7%</td>
<td>5%</td>
<td>3%</td>
<td>2%</td>
</tr>
<tr>
<td>60 – 80 keV</td>
<td>61%</td>
<td>27%</td>
<td>19%</td>
<td>12%</td>
<td>9%</td>
</tr>
</tbody>
</table>

For M-class flares, sensitivity levels of 20-40% may still be achievable in the lowest energy bands.
Candidate Flare Events

There have been several X-class flares since the launch of RHESSI. The best candidate for polarization studies was the X4.8 event of 23-July-2002, which showed a large signal in the rear segments.
Nature of the RHESSI Data

Rear Segment Data
(20 – 40 keV)

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

Germanium Spectrometer Array

Coolant Tank
Be Scattering Block
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
Normalization factors correct for relative detector efficiencies.
“Background” Subtracted Data

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

Systematic effects still need to be understood.
First Results

23 July 2002 : 20-40 keV

R (20-40 keV) \approx R (40-60 keV)

R (20-40 keV) > R (40-60 keV)

R (20-40 keV) < R (40-60 keV)
Summary

- Addition of a Be scattering block provides HESSI with significant polarimetric capability.
- Polarization sensitivity predicted to be less than a few percent for some X-class flares.
- First preliminary results are inconclusive. More work needed.

**Work in progress:**

1. Extension of current analysis to cover more events.
2. Incorporate simulation of Earth-scattered flux.
3. Expand the analysis to include all relevant detectors.
4. Investigation of polarization sensitivity for non-solar sources (gamma-ray bursts and the Crab pulsar).