HARD X-RAY SOLAR FLARE POLARIMETRY WITH RHESSI

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ABSTRACT

Although designed primarily as a hard X-ray imager and spectrometer, the Ramaty High Energy Solar Spectroscopic Imager (RHESSI) is also capable of measuring the polarization of hard X-rays (20–100 keV) from solar flares. This capability arises from the inclusion of a small unobstructed Be scattering element that is strategically located within the cryostat that houses the array of nine germanium detectors. The Ge detectors are segmented, with both a front and rear active volume. Low energy photons (below about 100 keV) can reach a rear segment of a Ge detector only indirectly, by scattering. Low energy photons from the Sun have a direct path to the Be and have a high probability of Compton scattering into a rear segment of a Ge detector. The azimuthal distribution of these scattered photons carries with it a signature of the linear polarization of the incident flux. Sensitivity estimates, based on simulations and in-flight background measurements, indicate that a 20–100 keV polarization sensitivity of less than a few percent can be achieved for X-class flares. The initial results from an analysis of data from the solar flare of 23 July 2002 indicate some modulation of the Be-scattered flux, but whether the modulation arises from polarization effects or whether it represents some instrumental effect is as yet unclear.

INTRODUCTION

Hard X-ray emission from solar flares, like any other form of electromagnetic radiation, has four, and only four properties. Each photon can be completely characterized by its time of arrival, its energy, its direction of arrival, and its polarization state. RHESSI is capable, to varying degrees, of determining all four of these quantities. The first two of these properties (time of arrival and energy) are measured directly as photon interactions in the Ge detectors. The third and fourth properties (arrival direction and polarization state) are determined through an analysis of the grouping of photons in time at each detector. RHESSI is capable of providing information on the linear polarization of photons between roughly 20 and 100 keV (McConnell et al. 2002). The study of polarization at hard X-ray energies is especially appealing in that the hard X-ray emission from any bremsstrahlung source (such as a solar flare) will be polarized if the phase-space distribution of the emitting electrons is anisotropic. Polarization measurements therefore provide a direct handle on the extent to which the accelerated electrons are beamed, which, in turn, has important implications for particle acceleration models.

Many models of nonthermal (e.g., thick target) hard X-ray production predict a clear and significant polarization signal, with polarization levels $> 10\%$ (e.g., Brown 1972; Langer and Petrosian 1977; Bai and Ramaty 1978; Emslie and Vlahos; Leach and Petrosian 1983; Zharkova et al. 1995; and Charikov et al. 1996). The precise level of polarization depends on both energy and viewing angle. Even thermal models of the hard X-ray source predict a finite polarization of order a few percent, due to the anisotropy in the electron distribution function caused by a thermal conductive flux out of the emitting region into the cooler surroundings (Emslie and Brown 1980). The thermal component, with its rather low polarization, tends to dominate the emission from all flares at energies below about 25 keV. At these energies, it therefore becomes difficult to distinguish the non-thermal component, with its intrinsic directivity signature, from the thermal component. This has led to the argument that polarization measurements can best be performed at higher energies (Chanan et al 1988).

The basic physical process used to measure polarization in the 20–100 keV energy range is Compton scattering. For a given value of the Compton scattering angle (θ), the scattering cross section for polarized radiation reaches a minimum in the direction parallel to the incident electric field vector ($\eta = 0^\circ$) and a maximum in the direction perpendicular to the incident electric field vector ($\eta = 90^\circ$). In other words, photons tend to be scattered at a right angle with respect to the incident electric field vector. The ultimate goal of a Compton scatter polarimeter (such as RHESSI) is to measure the azimuthal modulation pattern of the scattered photons. The amplitude of the modulation pattern provides information on the *magnitude* of the linear polarization. The minimum of the modulation pattern indicates the *direction* of polarization.

The first measurements of X-ray polarization from solar flares (at energies of $\sim$ 15 keV) were made by Soviet experimenters using polarimeters aboard the Intercosmos satellites. Polarization values in the range of $\sim 20\%$ to $\sim 40\%$ were reported (Tindo et al. 1970, 1972a, 1972b). These reports were met with considerable skepticism, on the grounds that they did not adequately allow for detector cross-calibration issues and limited photon statistics (Brown et al. 1974). Subsequent observations with an instrument on the OSO-7 satellite seemed to confirm the existence and magnitudes of the polarizations ($\sim$ 10%), but these data were compromised by in-flight gain shifts (Nakada et al. 1974). In a later study using a polarimeter on Intercosmos 11, Tindo et al. (1976) measured polarizations of only a few percent at $\sim$ 15 keV for two flares in July 1974. This small but finite polarization is consistent with the predictions for purely thermal emission that contains an admixture of polarized backscattered radiation (Bai and Ramaty 1978). A small polarimeter was flown on an early shuttle flight (STS-3) (Lemen et al. 1980) and made measurements of eight C- and M-class flares in the 5–20 keV energy range. Upper limits in the range of 2.5% to 12.7% were measured, although contamination of the Li scattering material invalidated the pre-flight calibration (Tramiel et al. 1984).

The ability of RHESSI to make polarization measurements, coupled with its ability to (independently) image the hard X-ray emission, provides a powerful tool for studying electron acceleration in solar flares. In addition, RHESSI will be able to make polarization measurements at energies higher than previous studies, where thermal emission may be less of an issue. Here we will summarize the status of our first efforts to analyze the polarimeter mode data from RHESSI.

RHESSI AS A COMPTON POLARIMETER

The heart of the RHESSI imaging system (Lin et al. 2002) consists of an array of nine segmented Germanium detectors (Smith et al. 2002). Each detector is made from a single germanium crystal, which is electrically divided into independent front and rear segments to provide an optimum response for low and high energy photons, respectively. This provides the equivalent of a $\sim$ 1 cm thick planar Ge detector (the front segment) in front of a thick $\sim$ 7 cm coaxial Ge detector (the rear segment). The front segment thickness is chosen to stop photons incident from the front (solar-facing side) of the instrument up to $\sim$ 100 keV, where photoelectric absorption dominates, while minimizing the active volume for background. Solar photons with energies from $\sim$ 100 keV to $\sim$ 20 MeV, including all nuclear gamma-ray lines, stop primarily in the thick rear segment alone. The intense 3–100 keV X-ray fluxes that usually accompany large γ-ray line flares are absorbed by the front segment, so the rear segment will always count at moderate rates. Photons with energy above 20 keV from non-solar sources can penetrate the thin aluminum cryostat wall from the side and also be detected by the Ge detector rear segments.

RHESSI is a spinning spacecraft, with a spin rate of $\sim$ 15 rpm. The high angular resolution imaging capability of RHESSI imposes severe requirements on the knowledge of the instrument orientation direction at any given time. Two spacecraft systems provide the necessary aspect solution (Fivian and Zehnder 2002; Hurford and Curtis 2002). A solar aspect system provides knowledge of Sun center in pitch and yaw to 1.5 arcsec. A star scanner is used to determine the spacecraft roll angle with an accuracy of $\sim$ 1.0 arcmin. The energy and arrival time of every photon, together with spacecraft orientation data, are recorded in the spacecraft's on-board memory for subsequent telemetry to the ground.

For the purposes of making polarization measurements, a small beryllium scattering block (3 cm in

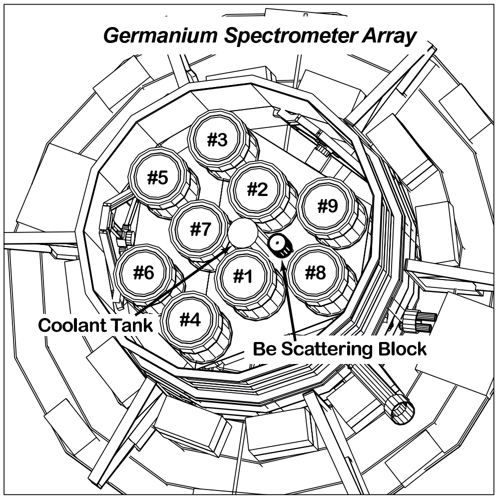

Fig. 1. The RHESSI spectrometer array as depicted by the GEANT mass model used for simulations.

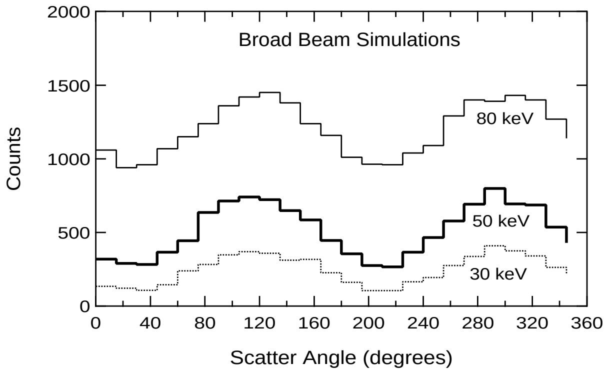

Fig. 2. The modulation patterns derived from simulations for three different energies (30, 50 and 80 keV). As energy increases, the total number of detected events increases, but the modulation factor decreases as a result of scattered photons.

diameter by 3.5 cm long) was placed within the spectrometer cryostat, near the center of the Ge detector array (Figure 1). The role of the Be block is to Compton scatter the solar flare hard X-rays (20–100 keV) into the rear segments of the adjacent Ge detectors. The graded-Z shield in front of the cryostat insures that solar flare photons of this energy which enter the cryostat will interact either in the front surface of a Ge detector or in the Be block. The segmented design of each Ge detector further insures that there are no direct solar flare photons in the rear segments within the 20–100 keV energy range. Flare photons within this energy range can only reach the rear segments by first scattering within the Be block. The distribution of events scattered into the adjacent Ge detector rear segments (with respect to some fixed reference frame) provides a polarization signature, since the direction of the scattering depends on the orientation of the electric field vectors, or plane of polarization, of the incoming photons. The spacecraft rotation provides a means to reduce the impact of systematic differences in detection efficiency amongst the different Ge detectors and to increase the sampling frequency with respect to the azimuthal scatter angle (η). There is, however, a significant background from higher energy flare photons which scatter into the rear segments from other parts of the spacecraft and from flare photons which reflect off the Earths atmosphere (the Earth albedo flux). Photons that scatter into the Ge detectors from other parts of the spacecraft will generally not vary with spin angle. This unmodulated component will interfere with the polarization measurement by effectively reducing the modulation factor (McConnell et al. 2002).

In principle, each of the nine Ge detectors provides a polarization signature. However, the quality of the signature varies, depending on the distance of the detector from the Be scattering block and the extent to which that detector is blocked from view with respect to the Be (for example, by other Ge detectors). Furthermore, the Ge detectors that are furthest from the Be do not generally provide a polarization signature with sufficient signal-to-noise to be useful in polarization studies. The Ge detectors that are most useful in polarization studies are detectors 1, 2, 8 and 9 (c.f., Figure 1). Unfortunately, detector 2 is currently not operating in segmentation mode and is therefore not usable for polarization studies.

The albedo flux poses a potentially significant problem in that the level of albedo flux reaching a given Ge detector can vary significantly with spin phase (depending on the orientation of the spacecraft with respect to the local zenith). The magnitude of the albedo flux can be quite large, as much as 40–50% of the direct solar flare flux at energies below 100 keV. Fortunately, the albedo flux has only 1 maximum per spin period instead of the two maxima exhibited by the polarization signal and can therefore be recognized using an appropriate analysis.

RHESSI SENSITIVITY TO SOLAR FLARE POLARIZATION

To simulate the polarimetric response of RHESSI, we use a modified version of the GEANT3 code that includes the effects of polarization in Compton scattering and tracks the polarization of the primary photon. The simulated mass distribution includes not only the RHESSI spectrometer, but also the complete telescope assembly, supporting electronics, the spacecraft support structure and the solar panels. A broad incident beam (60 cm diameter) insures that the effects of scattered photons (those that scatter into rear Ge segments from spacecraft components other than the Be) are properly modeled. Scattered photons carry no polarization signature and serve only to increase the level of background. Figure 2 shows the modulation patterns for three different energies (30, 50 and 80 keV), as derived from the simulations. Above about 50 keV, scattered photons become increasingly important. At energies near 100 keV and above, scattering completely dominates the response. In a source-dominated measurement, the efficacy of the RHESSI polarimeter mode peaks near 60 keV (McConnell et al. 2002).

The measured instrumental background spectrum, along with the simulated polarimetric characteristics, can be used to estimate the polarization sensitivity for a typical solar flare. Unfortunately, it is difficult to define a typical solar flare to use as a baseline for estimating polarization sensitivities. The X-ray classification depends only on the *peak* X-ray flux. Therefore, the polarization sensitivity for a given class flare will depend not only on the X-ray class of the flare, but also on the duration of the event and the details of its flux variation during the event. We have previously (McConnell et al. 2002) made estimates of the polarization sensitivity based on a 'typical' X2 flare (Chanan et al. 1988), assuming various flare durations ranging from 20 seconds up to 500 seconds. These estimates indicated that RHESSI has a sufficient polarization sensitivity to measure the polarization of X-class flares down to a level of below 10% and, in some cases, below 1%. This level of sensitivity will be useful in constraining various models that have been published in the literature.

INITIAL STUDIES OF SOLAR FLARE POLARIZATION

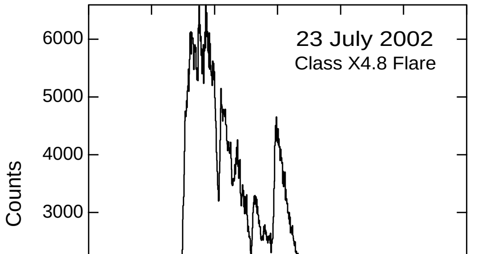

Fig. 3: Time history of the 23 July 2002 solar flare based on rear segment data in the 20–40 keV energy range.

The RHESSI spacecraft was successfully launched on February 5, 2002. During the first eight months of the mission, there have been 23 flares of class M5 or higher. We have surveyed these events, looking for events that showed a strong signal in the rear detector segments. By far, the event showing the strongest rear segment signal is the X4.8 class flare of 23 July 2002. Our initial studies have therefore concentrated on an analysis of this flare.

The 20–40 keV time history of this flare is shown in Figure 3. Our analysis covers the time period from 00:26 - 00:42 UT. Figure 4 shows the total counts in each rear detector segment as a function of azimuthal scatter angle, measured in a sun-fixed coordinate frame. (Detector 2 is excluded here because it is operating in an unsegmented mode.) The direction of the geocenter in each case is denoted by the vertical band near 140^o. The modulation is clearly dominated by atmospheric flux. Note that those detectors most shielded within the Ge array (detectors 1 and 7) show the least modulation.

A detailed analysis of the polarization signal from RHESSI will require simulations that incorporate the effects of scattered flux from the Earth's atmosphere. This work is in progress. Meanwhile, we have been working on a first order approach to the analysis that involves using only two of the three polarimeter mode Ge detectors. The idea is to use two homologous (or nearly-homologous) pairs of detectors (detector pairs 3/5 and 4/6) to derive background for the two polarimeter mode detectors (detectors 8/9). Since each pair of detectors is situated along the outer edge of the spectrometer array, the background detector pairs are expected to provide a good measure of the background in detectors 8/9 as a function of spacecraft roll angle, including the effects of atmospheric scattering. The different detection efficiencies of the various detectors (due, in part, to different sensitive volumes within the segmented detectors) must be accounted for in the

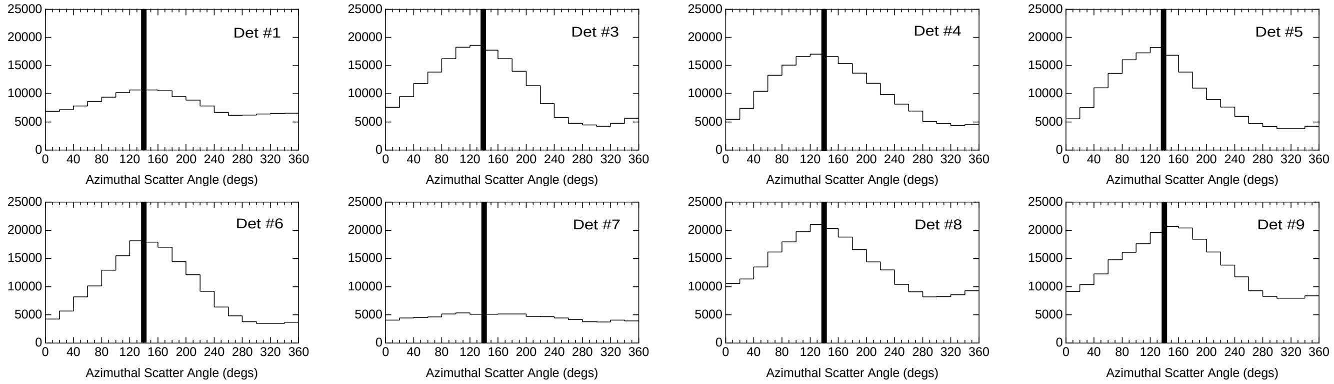

Fig. 4. Detector counts as a function of azimuthal scatter angle (in a sun-fixed coordinate system) for those eight detectors with an active rear segment. The modulation of the count rates is dominated by the atmospheric background. The vertical bars represent the direction of the geocenter.

analysis. In this case, we derived empirical correction factors for several broad energy bands based on an analysis from a non-flare period on 17 July 2002.

Figure 5 shows the scatter angle histogram that results from an analysis of the non-flare period in the energy band 20–40 keV. This plot represents a sum of the histograms for detectors 8/9 with background derived from detectors 3–6. As expected, the results are consistent with no net signal. Results from an identical analysis of the 23 July 2002 flare are shown in Figure 6. There is clearly evidence for events in the rear segments that have scattered from the Be block (since there is a net positive excess). The distribution of these events appears to be inconsistent with unpolarized hard X-rays, but it is also not consistent with that expected for polarized hard X-rays. (The solid line in Figure 6 represents the best-fit polarization signal.) Whether this modulation results from variability in the polarization angle or whether this is an artifact of some systematic effect in the data remains to be determined. We are continuing our efforts to develop a coherent picture of these data. Meanwhile we are also working to develop the procedures for a more expanded analysis of these data, incorporating the effects of atmospheric scatter and including the data from detector 1.

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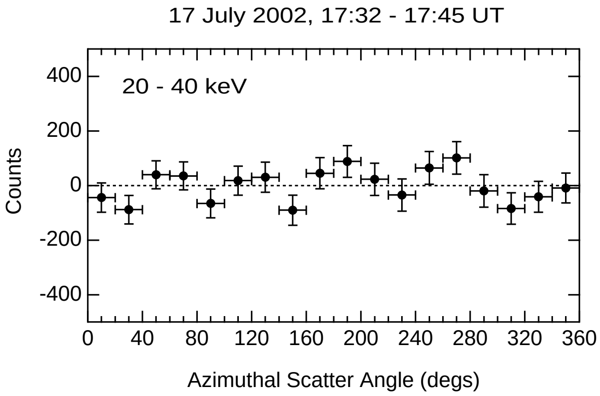

Fig. 5. Results from the analysis of a non-flare time interval on 17 July 2002. The plot shows background-subtracted detector counts as a function of azimuthal scatter angle (in a sun-fixed coordinate system) for detectors 8 and 9. All rear segment events between 20 and 40 keV are included.

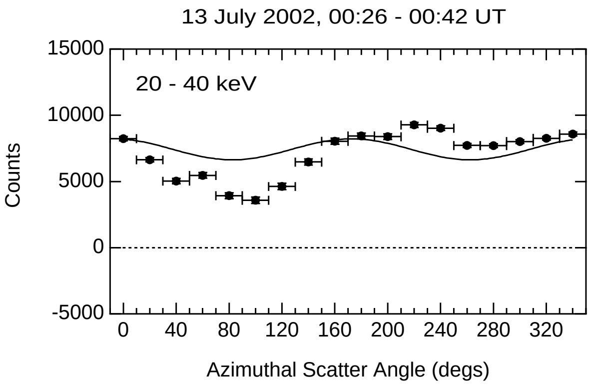

Fig. 6. Results from the analysis of the X4.8 flare on 23 July 2002 (Figure 3). The plot shows background-subtracted detector counts as a function of azimuthal scatter angle (in a sun-fixed coordinate system) for detectors 8 and 9. All rear segment events between 20 and 40 keV are included.

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