RHESSI INSTRUMENTAL LIMITS ON MEASUREMENTS OF THE GAMMA-RAY POLARIZATION FROM GRBS, SGRS AND SFS

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ABSTRACT

The Reuven Ramaty High Energy Solar Spectroscopic Explorer (RHESSI) satellite [1] with its 9 large Ge detectors may be used as a rotating gamma ray polarimeter. The polarization signal is extracted from the event-list using the Compton scattering technique in either a single or a coincidence mode. The polarimetric performance of RHESSI is discussed below for the coincidence mode applicable at energies above 120 keV. The results are based both on real RHESSI data and detailed Monte Carlo simulations. Out of about 400 Gamma Ray Bursts (GRB) detected by RHESSI to date, only 3 were suitable for polarization analysis. Values of the polarization (Π) range from 28% to 65% with errors larger than 40% (1σ). Studies of 7 strong Solar Flares (SF) give polarization levels between 2% and 50% with 1σ errors from 10% to 26%. The oscillating part of the giant flare of the Soft Gamma Repeater (SGR) SGR1806-20 on 27 Dec 04 was also observed but the number of Compton events from photons with energies above 120 keV was strongly limited due to its spectral softness.

1. MISSION AND ITS PAYLOAD

RHESSI was launched on the 5th Feb 2002 as the NASA SMEX mission into a circular Low Earth Orbit with about 590 km altitude and 38 degrees inclination. The satellite points to the Sun and rotates with a period of 4 seconds. Its instrumentation consists of the imager and Germanium spectrometer [2]. The primary goal of the mission is to provide high resolution images and spectra from Solar Flares in X-rays and γ-rays. The RHESSI spectrometer consists of 9 cylindrically shaped ultra high purity Ge-detectors cooled down to 75 K. It covers a wide energy range from 3 keV up to 20 MeV. Energy and time resolution are 1 keV (at 100 keV) and 1 μsec respectively. Germanium detectors have the diameter of 71 mm and the height of 85 mm. The inner electrode of each detector is split dividing it into two segments (front and rear) with the thickness of 15 mm and 70 mm respectively. In front of the spectrometer there is an imager made of two planes of grids with different thickness. Transmission coefficient of the grid system is about 50% for gamma rays with low energies. The total effective area from the front reaches up to 200 cm^2 for energies around 200 keV. The front segments are surrounded only by a ring of graded Z materials (Ta-Sn-Fe) with a total thickness of 2 mm. Rear segments have no shielding at all. Such an arrangement allows photons with energies above 25 keV to be detected from the side while photons with energies above 100 keV can be detected from all directions. The data are stored using the event-by-event mode and for each event the energy of the photon, its arrival time and detector number as well as the detector segment are stored onboard for further downlink. A large field of view of up to 2π as well as a big detector volume enables RHESSI for effective detection of GRBs and SGRs [3]. Typical detection rate of GRBs is 1-2 per week and to date RHESSI database consists of more than 400 GRB entries. Around 30% of its GRBs are also seen by the SWIFT satellite.

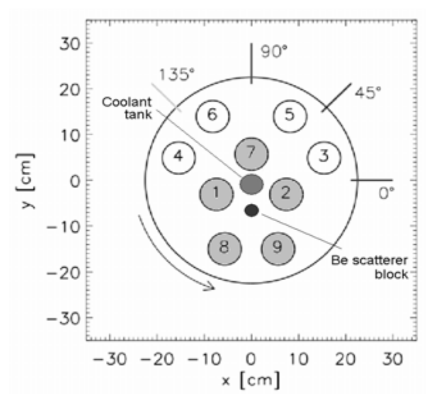

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Fig. 1. Arrangement of RHESSI detectors. All nearby pairs are used for coincidence measurements. Detectors filled dark measure photons from Be scatterer.

2. POLARIZATION MEASUREMENTS

Polarization measurements with RHESSI are possible using either a passive Beryllium scatterer at lower energies or coincidences between two close detectors at higher energies. Both methods utilise Compton scattering and take advantage of its polarization sensitivity reaching maximum for scattering angles around 90 degrees with respect to the incoming photon direction. Rotation of the satellite provides a way to get a clear modulation of the polarization signal and allows reduction of systematic effects e.g. from non-uniformities in the spacecraft mass distribution.

2.1 Passive Mode

The first method with the Be scatterer is applicable for photons coming parallel to the rotation axis and thus is used only for polarization studies of SF [4]. It is because the Be cylinder looks directly to the Sun through a corresponding opening being otherwise well shielded among Ge detectors. Although the modulation factors are high, this mode is oft contaminated with the Earth scattered photons that may dominate the signal.

2.2 Coincidence Mode

Polarization sensitivity of the coincidence mode is large for photon incoming angles up to 30 degrees from the satellite rotation axis for both front and rear direction [5]. This mode is applicable for energies higher than about 120 keV. One usually uses only the rear detector segments as the front ones are to a certain extend shielded by 2 mm of graded-Z absorber. The single energy threshold is set around 25 keV due to the detector noise. Solid angle for a pair of detectors in coincidence constrains further the extraction of events and limits it to nearby detector pairs only. Thus, out of 36 possible pairs of detectors just 18 are useful for analysis. Spacecraft rotation provides sampling of the scatter distribution between two detectors and is used to construct modulation curves and extract polarization signals.

2.3 Modulation Factor

Modulation factors μ_{100} of the RHESSI polarimeter are determined for each type of event using GEANT3 Monte Carlo simulations. The code is upgraded for tracing of the photon polarization. Values of μ_{100} depend both on the initial photon direction and energy.

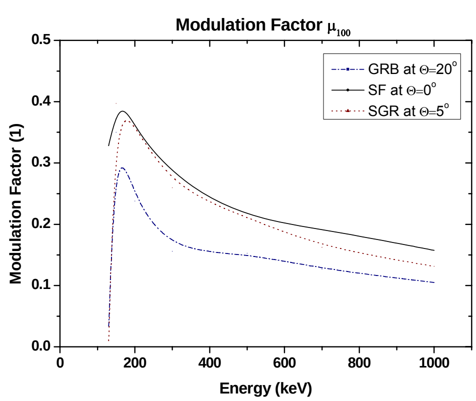

Fig. 2. Modulation factor of the RHESSI polarimeter as a function of photon energy for 3 incoming angles.

Thus, one firstly needs to know the angular position of the transient event and use it to apply the proper part of the response matrix in order to determine its energy spectrum. Position information for GRBs and SGRs is provided either via triangulation by the satellites Interplanetary Network [6] or is obtained using missions like SWIFT [7] that are able to resolve sky coordinates of the event. Modulation factor as a function of the photon energy is showed in Fig. 2 for three different directions (Θ) of incoming photons. The curves are related with SFs for Θ = 0°, with GRBs for Θ = 20° (GRB021206) and with SGRs for Θ = 5° (SGR1806-20). Maximum values of μ_{100} reach up to 40% at energies around 180 keV. Lower μ_{100} values at Θ = 20° indicate flattening of the modulation curve for events coming far from the spectrometer rotation axis.

2.4 Effective Area

In addition to the instrument modulation factor its effective area A_{eff} makes up a very useful parameter in measurements of the polarization. This quantity was computed taking exactly the same directions for SFs, GRBs and SGRs as in the μ_{100} case. Rotation of the satellite was also taken into account. The results are plotted in Fig. 3. It is seen that the effective area for polarization measurements for all three types of events depends strongly on the energy of incoming photons. Even at high energies A_{eff} reaches a few square cm only, reflecting a small value of the solid angle for detection of photons scattered between detectors. At lower energies, where intensity of the event is higher, values of A_{eff} come close to zero. It directly influences measurement accuracy as collecting the large number of events for analysis becomes more difficult.

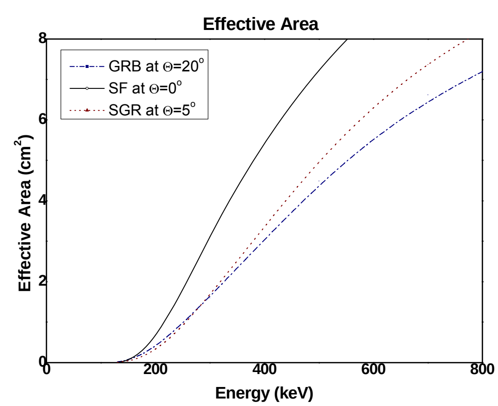

Fig. 3. Effective area of the RHESSI polarimeter vs. gamma-ray energy for three incoming angles.

One can see that the μ_{100} values for SGR are closer to these from SFs while the SGR A_{eff} values resemble more those from GRBs. It can be explained by higher absorption of photons coming at the angles Θ ≈ 5° caused by telescope grids and their socket mounts.

3. BACKGROUND

There are three main sources of the background distorting polarization measurements in the coincidence mode: (1) the real background from gamma rays generated e.g. by cosmic rays in the spectrometer itself and in other spacecraft materials, (2) accidental coincidences from independent photons detected simultaneously in two detectors and (3) event-related true coincidences from the photons that are scattered in the Earth atmosphere [8].

Due to rather large width of the coincidence time equal to 1 μsec, all intensive events are dominated by accidental coincidences. It is possible to subtract them using the delayed coincidence technique applied to the event list.

In the case of long events with low-to-moderate flux, the dominating source of the background comes from the real coincidences of photons related rather to the cosmic rays than to the event itself. Measurements of this background are performed using periods before or after the event or by an interpolation from two neighbouring and noise-free orbits.

In either case the signal to background ratio is predominantly smaller than one. It directly implies domination of the background and larger statistical errors for the polarization.

The scattering in the Earth atmosphere can easily contaminate single event spectra in the energy region up to about 250 keV. After applying the kinematical cut during extraction of coincidences the contribution of such photons drops below 8%.

4. MINIMUM DETECTABLE POLARIZATION

The Minimum Detectable Polarization MDP is defined in terms of the source and background rates. The event signal rate R_{coi} depends on the small effective area (0.5 - 2. cm^2) of the spectrometer for detection of coincidences [4,5]. The background rate is a sum of the real (R_{bckg}) and accidental (R_{acc}) events. Both R_{bckg} and R_{acc} are proportional to the large effective area of the spectrometer for detection of single photons, with a typical value of about 200 cm^2. The formula for MDP is given in Eq. 1 and the additionally used symbols are: μ_{100} ÷ modulation factor, n_σ ÷ number of standard deviations (σ), T ÷ event duration.

$$MDP = \frac{n_\sigma}{\mu_{100} \cdot R_{coi}(A_{eff}^{coi})} \cdot \sqrt{\frac{2 \cdot (R_{coi}(A_{eff}^{coi}) + R_{acc}(A_{eff}^{sng}) + R_{bckg}(A_{eff}^{sng}))}{T}} \quad (1)$$

Using predefined and most favorable characteristics for SFs, GRBs and SGRs like their spectral hardness, duration and total energy flux we generated the best values expected for MDP. The results are presented in Table 1. In the best case, the MDP for SFs is on the level of 10% to 15% while for GRBs it rises to 35% - 40% on the 1σ level. It was found that SGRs can be hardly studied as their R_{coi} is usually too small (R_{coi} ≈ 0.1/s). It is due to a very soft energy spectra and not sufficient number of photons with energies above 120 keV even for extremely strong events like the SGR1806-20 giant flare from 27 Dec 2004.

Table 1. Description of polarization candidates.

Event type	GRB	SF	SGR
Energy (keV)	100-1000	100-350	100-350
Power index (1)	2	3	6
Polar angle (deg)	20	0	5
Fluence(erg/cm^2)	$2.0 \cdot 10^{-4}$	$1.2 \cdot 10^{-3}$	$9.9 \cdot 10^{-5}$
Duration (sec)	1	200	400
Area single (cm^2)	177	282	82.2
Area coinc. (cm^2)	2.19	0.698	0.061
Mod. Factor (%)	14.6	31.7	45.7
Signal events (1)	1308	4165	36.3
Background (1)	64	4420	8840
Accidentals (1)	180	512	1
MDP-1σ (%)	35.	10.	700.

5. GAMMA RAY BURSTS

RHESSI detects GRBs with high efficiency of more than six confirmed observations per month (see http://grb.web.psi.ch). Less than one burst per month is close enough to the rotation axis to make searching for polarization signal realistic.

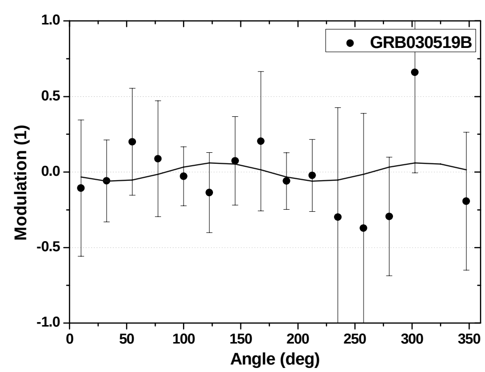

Fig. 4. Modulation data and fitted polarization curve for the GRB030519B burst.

In addition, the event must also have sufficient spectral hardness with high number of photons at energies above 120 keV. These two factors are necessary in order to deal with RHESSI moderate $\mu_{100} \approx 0.2$ and small $A_{eff} \approx 2$ cm^2. Number of Compton events needed to reach MDP of 40% on 1σ level is roughly equal to 1000. During its 5 years in space RHESSI detected only 3 such GRBs. Therefore there are no constrains yet on the polarization level in GRBs that could be deduced to date from the RHESSI measurements [3]. Earlier claims about high GRB polarization detected by RHESSI [10] were later on revised as premature [3].

6. SOLAR FLARES

Although RHESSI detected a large quantity of X-class flares, the number of events suitable for polarization analysis at higher energies is rather restricted. Good candidates should have a strong non-thermal component and no contamination with particles from Coronal Mass Ejections. In addition, the flare should be preferably positioned close to the limb where one expects higher polarization signals. The most suitable section of the flare is anticipated to be in the initial explosive part where magnetic fields might be better aligned. To date, we found only about 10 good candidates fulfilling above criteria. The analyzed data set consists of 6 X-class and 1 M-class SF. Polarization was looked for in the energies 100 keV to 350 keV as in the most cases a wider range was followed by big increase of the background. SF polarization degrees found in the analysis are between 2% and 50% with 3σ errors from 30% to 75% [9]. These results allow for rejection of polarization levels with values that are higher than 60% with χ^2=2.7/dof.

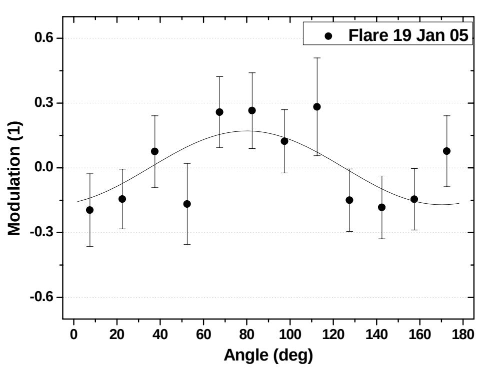

Fig. 5. Polarization data and fitted modulation curve for SF from 19 Jan 2005.

7. SOFT GAMMA REPEATERS

The Giant Flare from the SGR1806-20 on 27 Dec 2004 was detected very close to the spacecraft rotation axis: $\Theta = 5.3°$. Although the prompt peak saturated the RHESSI spectrometer one could obtain a good signal from the oscillating part. In the energy range from 100 keV to 350 keV about $3.4 \cdot 10^5$ events were collected. Using events from the front detectors, a fit of the SGR spectrum was performed. Good data description was found for the power law function with a spectral index $\gamma \approx -6$. Unfortunately, the number of Compton events in the rear detectors was not only very small but also many photons were coming from the side after being scattered in the Earth atmosphere. Therefore no polarization predictions for the SGR giant flare on 27 Dec 2004 were possible. The same conclusion is valid for other SGRs as their observed spectral power is weaker than SGR1806-20.

8. SUMMARY

RHESSI with its 9 large, weakly shielded detectors can be used to measure polarization of hard X-ray sources located near to its rotation axis. Polarization signal for energies above 120 keV is extracted using Compton scattering coincidences between close detector pairs. Peak value of the modulation factors μ_{100} reaches 40% at ca. 180 keV for events on the rotation axis. Unfortunately the polarimeter performance is strongly reduced by its very small effective area $A_{eff} \approx 1$ cm^2. Accidental coincidences as well as the real-time background not related with the event are major sources of errors. Even for the best polarization candidates the background dominates over the signal strongly limiting the MDP. For the largest SF the MDP values are below 15% but the best levels for GRB are only 40% (1σ). Improvement by a factor of more than 10 is needed in order to pin down physical processes involved in the energy release. It will require a smaller coincidence time and larger number of detectors able to cover a wide field of view.

9. REFERENCES

1. R.P. Lin et al., 2002, *Solar Phys.* 210, 3
2. D.M. Smith et. al., 2002, *Solar Phys.* 210, 33
3. C. Wigger et. al., 2004, *Astrophys. J.* 613, 1088
4. M.L. McConnell et al., 2002, *Solar Phys.* 210, 125
5. W. Hajdas et. al., 2005, *Il Nuovo Cimento*, 28C, 817
6. K. Hurley et al., 16-20 February 2004, Munich. *Proceedings of the 5th INTEGRAL Workshop*, 645
7. N. Gehrels et al., 2004, *Astrophys. J*, 611, 1005
8. W. Hajdas et al., 16 – 23 July 2006 Beijing, *36th COSPAR Scientific Assembly*, E2.3-0086-06
9. E. Suarez et al., 2006, *Solar Phys.*, 239, 149
10. S. Boggs et. al., 2003, *Nature,* 423, 415