IL NUOVO CIMENTO Vol. 28 C, N. 4-5 Luglio-Ottobre 2005
DOI 10.1393/ncc/i2005-10161-x

RHESSI as Gamma Ray Burst Polarimeter(*)

W. Hajdas, C. Wigger and A. Zehnder
Paul Scherrer Institut, CH-5232 PSI Villigen, Switzerland

(ricevuto il 23 Maggio 2005; pubblicato online il 20 Ottobre 2005)

Summary. — The Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) was designed to measure hard X-rays and γ-rays from solar flares. With its big detection area and thin side shielding it also proved to be well suited for studying Gamma Ray Bursts (GRB). Polarization analysis is feasible as well, due to a big modulation factor (MF), though serious constraints on the minimum detectable polarization (MDP) come from detection efficiency of double scattered photons. More constraints are given by background of accidental and real coincidences.

PACS `95.55.Ka` – X- and γ-ray telescopes and instrumentation.
PACS `95.75.Hi` – Astronomical polarimetry.
PACS `95.85.Pw` – Gamma-ray astronomical observations.
PACS `98.70.Rz` – γ-ray sources; γ-ray bursts.
PACS `01.30.Cc` – Conference proceedings.

1. – Introduction

Data analysis of astronomical objects typically uses spectral characteristics and time variability in order to derive physical properties of the source. It often results in ambiguous explanations by several "equally good", but different models. The measurement of photon polarization may give us an additional tool to pick the best one. It also enables us to study various astrophysical phenomena and permits us to distinguish between photons coming from synchrotron radiation, Compton scattering or bremsstrahlung. To date, the only positive and conclusive results from various γ-ray polarization measurements in space are for the Crab nebula. It is largely due to technical difficulties with γ-ray polarimetric measurements. Nonetheless, in the past few years several novel astronomical γ-ray polarimeters were proposed, aiming to provide first successful polarization data. Here we report results of our studies of the polarization detection potential with the already flying RHESSI satellite [1] and its germanium spectrometer. The mission is equipped with a passive beryllium scatterer for measurements of the solar photon polarization [2]. In this paper we concentrate on polarization studies for non-solar sources (like GRBs) using a double scattering, coincident mode in which one detector acts as an active scatterer and the other one as an analyzer.

(*) Paper presented at the "4th Workshop on Gamma-Ray Burst in the Afterglow Era", Rome, October 18-22, 2004.

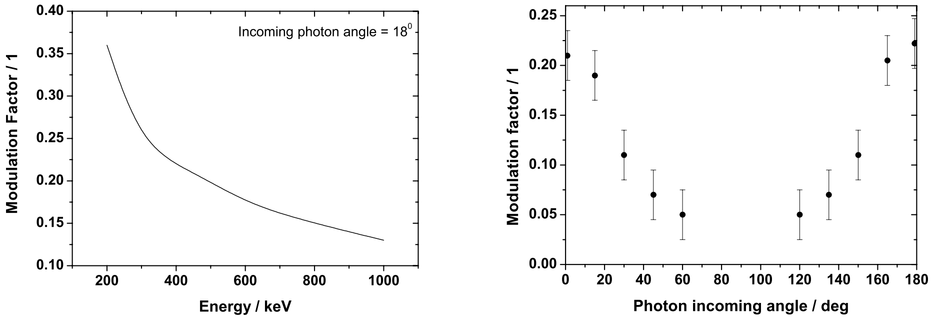

Fig. 1. – Modulation factor as a function of the initial photon energy (left) and the photon incoming angle (right).

2. – RHESSI and its spectrometer

RHESSI was launched into a Low Earth Orbit on 5th February 2002. It is a NASA SMEX mission devoted to observation of solar explosive phenomena and providing γ-ray dynamic images of solar events. The satellite permanently points toward the sun and rotates with a period of about 4 s. Its mass is equal to 238 kg including 120 kg of scientific payload. There is only one instrument on board consisting of the imager- telescope system and Ge-spectrometer [3] detecting photons with energies from 3 keV up to 20 MeV. The spectrometer has nine super-pure Ge-detectors ($\phi = 7.1\,\text{cm}$, $h = 8.5\,\text{cm}$) working in the event-by-event mode. Photon arrival time, deposited energy and a number for the detector segment hit define each detected event. The energy and time resolution ($\Delta E \approx 3\,\text{keV}$, $\Delta t \approx 1\,\mu\text{s}$) allow for time-resolved spectroscopy. Polarization measurements are also possible using the photon event list and a coincidence mode between two nearby detectors. Due to a thin side shielding γ-rays from all directions are detectable. The effective solid angle for observations of the GRBs is half the sky and the energy range for their detection is between ca. 100 keV and a few MeV. Usually, more than 5 GRBs per month are observed.

3. – Response and analyzing power modelling

Response and analyzing power calculations were performed using the complete satellite mass model based on the GEANT3 code from CERN. The Ge-spectrometer and its nearest surroundings were described with a high level of accuracy while for more distant parts some approximations were used [4]. Polarization sensitive processes (Compton) and corresponding tracing routines were implemented using the GEANT4 approach. It allowed us to generate detector responses for photons with predefined energies, incoming angles and polarization vector directions. Information about the incoming photon polarization could be extracted using coincident events between two detectors. It was shown that for typical spectral distributions of the GRB, the relative number of such events (multiplicity = 2) is only about 1–2 %. This is a direct consequence of two factors: low mean free path values for γ-rays of a few hundred keV energy in Germanium and small values of the solid angle for photon scattering from one Ge-detector to another. Thus,

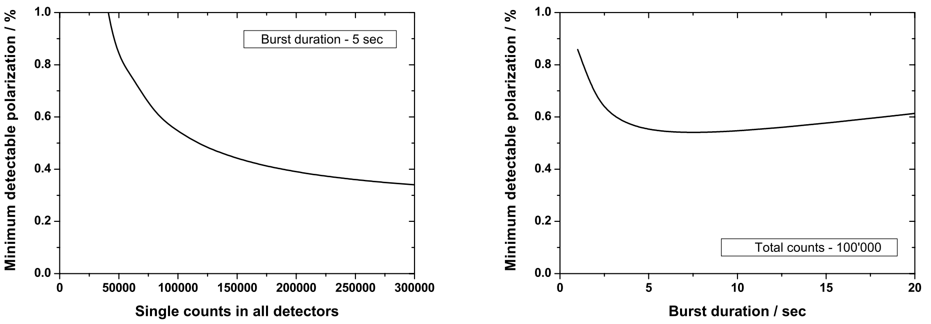

Fig. 2. – Minimum detectable polarization (2σ) as a function of the number of detected photons (left) and burst duration (right). ($f(E) = c \cdot E^{-2}, E \in (25 - 2000)\,\mathrm{keV}$, background included).

despite the dominating role of the Compton cross section for energies above 150 keV, a very strong event is still required for a statistically significant result. In the next step we extracted the RHESSI MF by utilizing the satellite rotation and comparing the relative number of coincidences between perpendicular detector pairs.

The low energy threshold imposed on the single detector for the polarization analysis with RHESSI is usually around 25–30 keV. It corresponds to an energy threshold of the incoming photon of around 150 keV. These criteria were applied to compute the RHESSI MF and its energy dependence. As one can see in fig. 1, the MF is highest at low energies. Thus, the best burst candidates for RHESSI polarization analysis should have most counts at lower energies and be very strong. Typical MF values for GRBs coming close to the satellite rotation axis are around 0.2.

Calculations point out that the modulation curve is well preserved for polarized bursts coming from within about 25° of the RHESSI rotation axis (front and rear). In this region the MF changes less than 30 %. At other angles the curve flattens and the analyzing power rapidly decreases. The MF dependence on the photon incoming angle is shown in fig. 1. One expects to detect about 10 GRBs/year with directions close to the satellite rotation axis and thus suited for the polarization analysis [5].

4. – Background sources

Three different sources of background come into consideration while extracting the RHESSI GRB modulation curve. The real coincidences background is exhibited as true coincident events between detectors, and its sources are diffuse background photons and γ-rays generated by cosmic-ray–induced nuclear reactions. After applying cuts on the photon energies and setting the coincidence time width between detectors (usually 1 μs), its rate is relatively constant and amounts to about 120 events/s. It can be dominant for very long but less intense bursts. The second background source comes from accidental coincidences. It is directly related to the GRB intensity, being a product of two single detector rates multiplied by their coincidence time width. Such a quadratic function of the rate makes it a dominant background source for very strong GRB events. Although the accidental background can be measured accurately, it effectively increases the MDP value. The last source of background depends on the event geometry with respect to the

Earth and the spacecraft itself. It is caused by photons initially re-scattered by the Earth atmosphere. As such photons may change their polarization direction, this background source decreases the observed value of the burst polarization. At the same time it also decreases the instrument response matrix and its MF value. It can be partially taken into account by proper modelling though the uncertainties are rather hard to control.

5. – Minimum detectable polarization

The MDP value is defined in terms of the source and background rates (R), the RHESSI MF, and the whole event duration T—see equation below.

$$MDP = \frac{n_\sigma}{MF \cdot R_{coi}(R_{sng})} \cdot \sqrt{\frac{2(R_{coi}(R_{sng}) + R_{accid}(R_{sng}) + R_{realbckg})}{T}}. \tag{1}$$

The multiplicative factor n_σ indicates the significance level. The background is a sum of real ($R_{realbckg}$) (*e.g.,* from photons generated by Cosmic Rays) and accidental (R_{accid}) coincidences. Both the coincidence signal rate R_{coi} and the accidental background rate R_{accid} are related with the single detector rate R_{sng}. Combining them allows us to generate the MDP curves as a function of the number of detected photons or the burst duration—see fig. 2. The curves were obtained for a coincidence time width of 1.5 μs and a ratio between coincident and single events equal to 0.015. The results are in accordance with the GRB polarization analysis from [6] and indicate rather limited polarimetric potential of the instrument even for the strongest bursts ($N_{sng} \approx 10^5$ events).

6. – Summary

The RHESSI spectrometer can be characterised by a large detection area and high energy and time resolution. Nonetheless, the effective area for polarimetric detection of double coincidences is much smaller. The average value of its MF is about 0.2 for events coming close to the axis. One can expect about 10 such events per year. However, after taking into account both real and accidental background, even for the strongest GRBs, the MDP values are high ($\sim 50\,\%$). This seriously limits the RHESSI usefulness as a GRB polarimeter. A novel device should be characterised by many smaller detectors but with larger total effective area for both single and double event detection. The coincidence width should be much lower than 1 μs and the lower energy threshold set at few tens of keV favouring higher values of the instrument MF.

REFERENCES

[1] Lin R.P. *et al.*, *Solar Physics*, **210** (2002) 3.
[2] McConnell M. *et al.*, *Solar Physics*, **210** (2002) 202.
[3] Smith D. *et al.*, *Solar Physics* , **201** (2002) 33.
[4] Hajdas W. *et al.*, PSI Annual Report 2001.
[5] See `grb.web.psi.ch`.
[6] Wigger C. *et al.*, *ApJ*, **613** (2004) 1088 , see also Wigger C. *et al.*, these proceedings (2005).