Solar Particle Event Analysis using the ESA Standard Radiation Environment Monitor and the Worldwide Neutron Monitor Network

Helen Mavromichalaki*, **Athanasios Papaioannou***, **Maria Gerontidou***
Ioannis Daglis†, **Anastasios Anastasiadis**†, **Ingmar Sandberg**†, **Kostas Tziotziou**†, **Ioannis Panagopoulos**†
Petteri Nieminen‡, **Alexi Glover**‡ **and Paul Bühler**‡
**Physics Department, University of Athens, Athens, Greece*
†*Institute for Space Applications and Remote Sensing National Observatory of Athens, Greece*
‡*European Space Agency, ESA European Research and Technology Centre (ESTEC), Netherlands*

Abstract. **Solar Energetic Particle events are a manifestation of violent energy release processes occurring in the solar atmosphere. The European Space Agency (ESA) has developed the Standard Radiation Environment Monitor (SREM), which is capable of detecting SEP radiation threats for space instrumentation. In this work, SREM measurements were used to identify a number of SEP events during Solar Cycle 23. An exhaustive study to correlate these identified events to their generating sources has been attempted. We have used available space and ground based data and in particular cosmic ray data from the worldwide network of neutron monitors. Calculations of the characteristics and special features of the identified events, such as anisotropy, amplitude and spectra as well as their registered impact on Earth have been performed. Finally, we also present an initial effort of correlating estimated SREM fluxes with the ground based measurements and setting specific criteria.**

Keywords: **solar energetic particles, interplanetary space, cosmic rays**

I. INTRODUCTION

Solar particle events (SPEs) are being observed as increases of the solar energetic particle (SEP) fluxes. Particles are being accelerated either at the Sun during a solar flare (SF) or at shocks in interplanetary space formed by a coronal mass ejection (CME). SPEs are categorized as impulsive and gradual according to their characteristics which strongly depend on the nature and the location of their source. Whatever their source, they pose a serious health risk to humans at space and at high altitudes flights and constitute a serious hazard for the micro-electronics and hardware parts of satellites, spacecrafts and aircrafts. The most hazardous are considered to be the gradual ones. The European Space Agency (ESA) has developed a solid state particle detector, the Standard Radiation Environment Monitor (SREM) [1]. It consists of three silicon detectors (D1, D2 and D3) in a two detectors head configuration. One system is a single silicon diode detector (D3) and the other one uses two silicon diodes (detectors D1/D2) in a telescope configuration. SREM is capable of detecting high energy protons (from $\sim$ 10 MeV to $\sim$ 300 MeV) and electrons (from $\sim$ 300 keV to $\sim$ 6 MeV) in a number of energy bins providing energy spectral information with a $\pm$ 20 ^{o} angular resolution. ESA created the SREM program and currently four SREM units are flying on space missions (PROBA-1, INTEGRAL, Rosetta, Giove-B), while other units will be included at future ones, including Herschel and Planck [2].

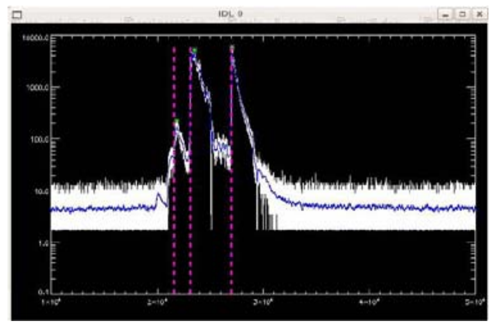

Fig. 1: IDL module for SREM data pre-analysis. Example event of January 2005

All of the currently flying units are operating well producing continuous data, useful for the analyses of the near-Earth and interplanetary space radiation environment [3], [4]. In this work, SREM measurements were used in order to identify SEP events during the time period 2003-2006. Correlative studies of these identified events to their generating sources have been attempted. We have used available space and ground based data including cosmic ray (CR) data from the worldwide network of neutron monitors [5]. Calculations of the characteristics and special features of the identified events, such as anisotropy, amplitude and spectra as well as their registered impact on Earth have been performed.

II. SREM DATA PRE-ANALYSIS

At the commencement of this effort, SREM raw data had to be filtered and converted into fluxes. The pre-analysis of the data was treated with the development of appropriate IDL modules (Fig. 1) that enable to detect several events and retrieve their characteristics, such

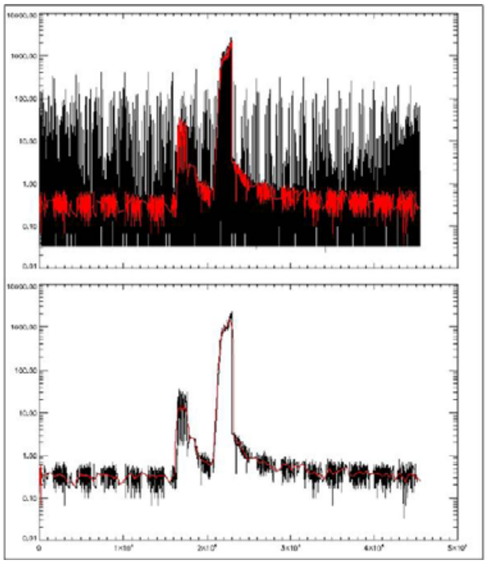

Fig. 2: An example of Radiation belt filtering

as local maxima, onset time and maximum flux. This resulted into a working list of SREM detected events.

A necessary step for SPE analysis is the filtering of SREM data for counts attributed to radiation belt (RB) crossings. For this reason SREM data associated with RB crossings where excluded and filled by power law interpolation. For the conversion of counts-to-fluxes the following integral equation has to be solved [6]:

$$CR_i = \int_{Emin}^{Emax} f(E) G_i(E)\, \mathrm{d}E \qquad (1)$$

From the SREM data pre-analysis a working list of SREM detected and filtered events was produced. A selection from these events led to case studies which were treated both from space based and ground based recordings.

Namely, these case studies included the events of October-November 2003, January 2005, September 2005 and December 2006. In specific:

A. *January 20, 2005 (GLE69)*

In the case of GLE69, SREM units recorded high proton fluxes. Using the raw data of INTERGAL and Rosetta satellites (Fig. 3) and by comparison to the ground based recordings we have been led to the observational fact that there is a time shift between the satellites and ground based recordings. A preliminary calculation of the time delay t between ground based and satellites recordings referring to the INTEGRAL one is given below:

$$\begin{aligned} Dt &= t_{INTEGRALmax} - t_{GLEonset} \\ &= 120\ min\ or\ 80\ min \end{aligned}$$

This difference in time lag is due to the fact that GLEs are highly anisotropic events. Thus, some stations record earlier than others the proton fluxes. The value of 80 min

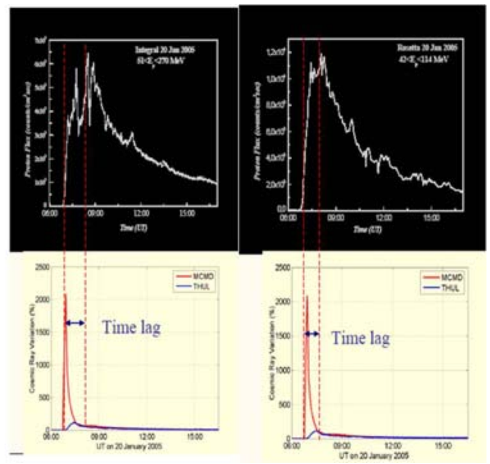

Fig. 3: The SREM INTEGRAL and Rosetta recordings compared to the recordings from McMurdo and Thule NM stations

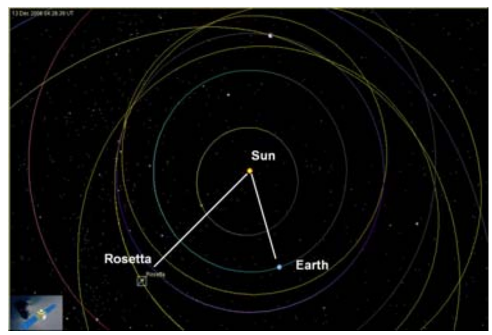

Fig. 4: Rosetta's position on December 13, 2006 with respect to the Sun and the Earth

corresponds to Thule NM station which was the station that registered last the maxima at 07:30 UT, while Dt =120 min corresponds to South Pole NM station which was the first to register the maxima at 06:50 UT [7]. The time lag (delay time) for Rosetta was:

$$\begin{aligned} Dt &= t_{Rosettamax} - t_{GLEonset} \\ &= 80\ min\ or\ 30\ min \end{aligned}$$

Again, 80 min corresponds to South Pole station and 30 min to Thule station.

B. *December 13, 2006 (GLE70)*

In this case, Rosetta did not record the event because of its distant position with respect to the source of solar activity (Fig. 4)

With the same treatment as before for INTERGAL and NM data, finding is:

$$\begin{aligned} Dt &= t_{INTEGRALmax} - t_{GLEonset} \\ &= 220\ min\ or\ 90\ min \end{aligned}$$

As before, the time of 220 min corresponds to Oulu station, which was the station that registered firstly the

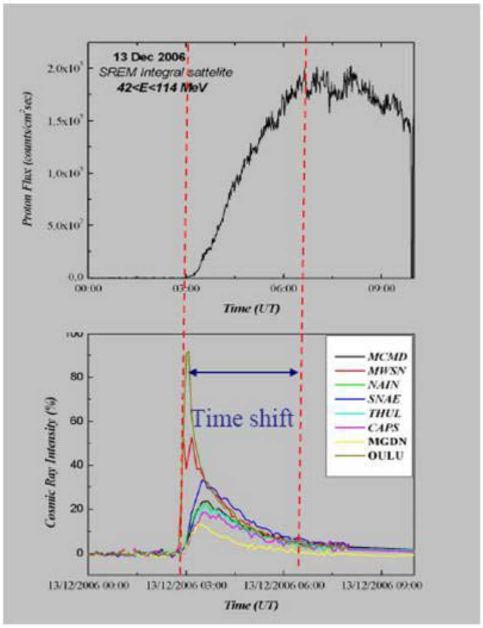

Fig. 5: The SREM INTEGRAL recordings compared to the recordings from eight (8) NM stations

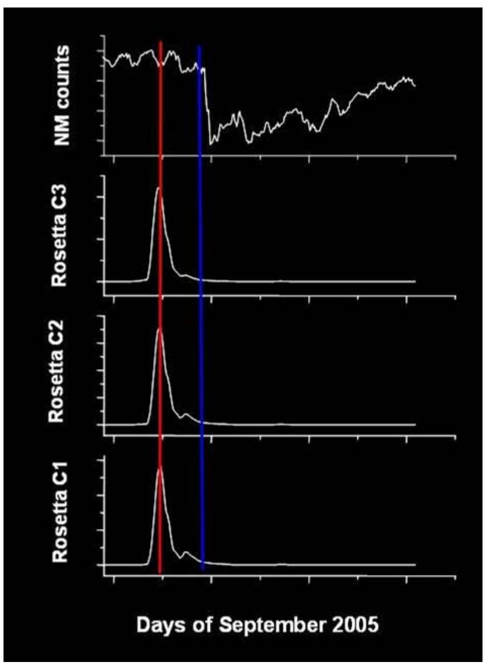

Fig. 6: The SREM Rosetta recordings compared to the Athens NM data for the case of September 09, 2005

maxima and the biggest increase (92%) and the time of 90min to Thule station.

C. September 09, 2005

This case is apparently different from the two previous ones. This is because, ground based recordings did not record an enhancement in count rate but a decrease. This effect is known in the CR community as a Forbush decrease (FD). For the case of September 2005, the FD was severe and long lasting [8]. Due to the relevant position of Rosetta to the solar region (AR 798),which was responsible for the solar activity during this period, SREM recorded particles arriving from the flare source. The corresponding shocks from CMEs magnetically shielded the Earth and an irregular FD was recorded. The red line indicates the maximum of the SPE while the blue line denotes the initiation of the Forbush decrease.

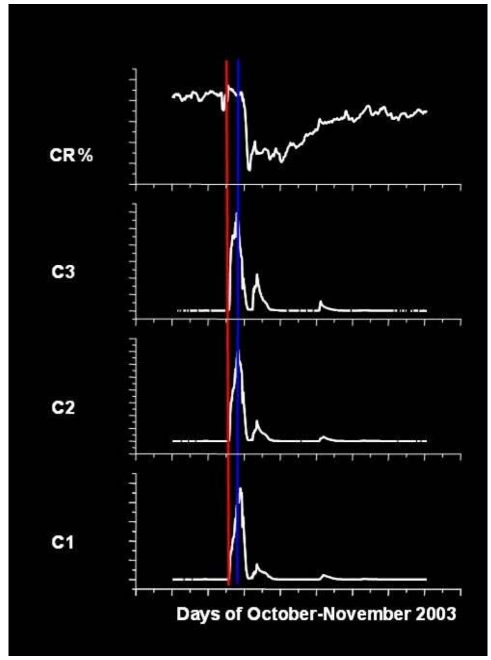

Fig. 7: The SREM INTEGRAL recordings compared to the Athens NM data for the case of October 29, 2003

D. October 29, 2003

A comparative plot of NM data versus various proton counters of SREM units has been produced for the astonishing period of October 2003 [9]. The available channels were: C1 ($42<E(\mathrm{MeV})<114$), C2 ($51<E(\mathrm{MeV})<270$) and C3 ($73<E(\mathrm{MeV})<418$). It is rather clear that the initiation of the SEP event is very close to the initiation of the Forbush effect (FE). It is worth mentioning that the most intense FD was registered on October 29, 2003. The SEP event recorded by the INTEGRAL SREM unit on October 28, 2003 (12:00 UT) and peaked on October 29, 2003 (01:00 UT). This is of course an expected scenario. Due to large amounts of solar plasma eruptions, the Earth was magnetically shielded with a significant rising in the magnetic pressure. This is the reason for a giant FD and it is actually verified by the intense solar activity that forehanded the decrease.

The red line indicates the onset time of the SPE. The blue one defines the 'moving' maximum of the SPE. By 'moving', is meant that according to the energy of the protons the maxima slightly changes. Also the maximum of the higher energy protons (C3) identifies itself with the CR precursor right before the initiation of the giant Forbush effect of October 29, 2003.

III. CONCLUSIONS

a. The most important result of this analysis is the fact that all events recorded by SREM units (for the particular case studies) were also recorded by ground based detectors (NMs).

b. It has been shown that for all GLE events (October 2003, January 20, 2005 and December 13, 2006) the onset was first recorded by NMs.

c. All FDs that were recorded by NMs also left their signature at SREM recordings. Specifically in the case of September 09, 2005 the onset of the SREM recordings prevailed the NM ones due to the relevant position of the satellite [10] and the solar source while on the case of October 29, 2003 the maximum of the higher energy protons identifies itself with the CR precursor right before the initiation of the giant FD.

Further investigation on correlative studies is necessary and will be implemented in the near future.

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REFERENCES

[1] A. Mohammadzadeh, E. Evans, P. Nieminen, E. Daly, P. Vuilleumier, P. Bühler, C. Eggel, W. Hajdas, N. Schlumpf, A. Zehnder, J. Schneider and R. Fear, (2003), *The ESA Standard Radiation Environment Monitor program first results from PROBA-I and INTEGRAL*. IEEE TNS, 50, pp. 2272-2275

[2] H. Evans, E. Daly, A. Mohammadzadeh and P. Nieminen, (2006), *ESA Radiation Monitors: On-going and planned activities*. Proc. Radiation Detection and Dosimetry Workshop, online at: http://srag-nt.jsc.nasa.gov/Publications/Publications.cfm

[3] W. Hajdas, P. Bühler, C. Eggel, P. Favre, A. Mchedlishvili and A. Zehnder, (2003), *Radiation environment along the INTEGRAL orbit measured with the IREM monitor*. Astron and Astrophys., 411, L43-L48

[4] Online at: http://srem.web.psi.ch/html/srem_publications.shtml

[5] H. Mavromichlaki, G. Souvatzoglou, C. Sarlanis, G. Mariatos, M. Gerontidou, A. Papaioannou, C. Plainaki, S. Tatsis, A. Belov, E. Eroshenko and V. Yanke, (2005), *The new Athens center on data processing from the neutron monitor network in real time*. Annales Geophys., 23, pp. 1-8

[6] H. Evans, P. Bühler, W. Hajdas, E. Daly, P. Nieminen and A. Mohammadzadeh, (2008), *Results from the ESA SREM monitors and comparison with existing radiation belt models*. Adv. Space Res., 42, pp. 1527-1537

[7] C. Plainaki, A. Belov, E. Eroshenko, H. Mavromichalaki and V. Yanke, (2007), *Modeling ground level enhancements: Event of 20 January 2005*. J. Geophys. Res., 112, A04102, doi:10.1029/2006JA011926

[8] A. Papaioannou, H. Mavromichalaki, E. Eroshenko, A. Belov and V. Oleneva, (2009), *The burst of solar and geomagnetic activity in August September 2005*. Annales Geophys., 27, pp. 1019-1026

[9] C. Plainaki, A. Belov, E. Eroshenko, V. Kurt, H. Mavromichalaki and V. Yanke, (2005), *Unexpected burst of solar activity recorded by neutron monitors during OctoberNovember 2003*. Adv. Space Res. , 35, pp. 691-696

[10] W.Keil, (2005), *Radiation Effects on Spacecraft and Countermeasures Selected Cases*. http://www.esa-spaceweather.net/spweather/workshops/eswwII/Session4/Presentation_KEIL.pps