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Solar Origin of Solar Particle Events Detected by the Standard Radiation Environment Monitor of ESA

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Abstract. Solar Particle Events (SPEs) of the 23rd Solar Cycle detected by the ESA Standard Radiation Environment Monitor (SREM) onboard the INTEGRAL satellite have been studied in order to find their connection to solar sources. X-ray, optical and radio data of solar flares that were observed by several space-based instruments during the aforementioned solar cycle have been selected. The data were reduced and thoroughly analyzed in order to establish the corresponding solar origin of the selected SPEs. The extensive scientific analysis has produced clear correlations with X class solar flares for the events of the October-November 2003, January 2005 and December 2006 periods while for the events that occurred during September 2005, correlations with X class flares are possible but not straightforward due to the complexity of the registered solar particle fluxes.

1. Introduction

Solar particle events (SPEs) are mostly associated with flaring activity in complex active regions on the surface of the Sun and/or with coronal mass ejections (CMEs) and interplanetary (IP) shocks driven by CMEs. SPEs associated directly with flares mostly originate from impulsive events at the western hemisphere, arrive to Earth as rapidly as some electromagnetic signatures (within tens of minutes to a couple of hours) and last for hours. SPEs which are mostly related to CMEs and IP shocks originate from fast CMEs (which may or may not be linked to solar flares), take from half a day to a couple of days to arrive to Earth and last for several days.

Solar flares are sudden, violent and very energetic explosions occurring in active regions around sunspots which are powered by sudden large changes of the local magnetic field topology through reconnection processes that result to huge releases of magnetic energy. This energy release leads to plasma heating, particle acceleration and mass transport and produces electromagnetic radiation across the electromagnetic spectrum at all wavelengths from long-wave radio to the shortest wavelength gamma rays. During a large solar flare, the X-ray flux increases by many orders of magnitude compared to the pre-flare X-ray levels.

2. The SREM Unit

SREM is a solid state detector developed in partnership between ESA, Paul Scherrer Institute (PSI) for Astrophysics and Contraves Space A.G.. It measures both electrons with energies above 500 keV and protons with energies above 10 MeV. So far, seven units have been launched on-board satellites STRV-1C, PROBA-1, INTEGRAL, ROSETTA, GIOVE-B and recently on HERSCHEL and PLANCK.

Table 1.: The proton flux as it was recorded by channel C1 of the SREM unit onboard *INTEGRAL* satellite for the maximum of the events.

Event	Onset		Maximum		Flux 43-86 MeV
number	Date	Time (UT)	Date	Time (UT)	(counts/cm^2/s)
1	26/10/2003	19:16:46	27/10/2003	04:24:54	104.23
2	28/10/2003	11:36:47	29/10/2003	03:40:47	27055
3	29/10/2003	18:22:37	30/10/2003	02:47:40	5132.5
4	02/11/2003	17:45:29	02/11/2003	22:23:04	1769.29
5	05/11/2003	04:08:46	05/11/2003	05:38:58	189.55
6	15/01/2005	06:40:12	15/01/2005	16:46:27	14.60
7	16/01/2005	05:26:02	16/01/2005	16:27:24	220.14
8	17/01/2005	13:52:04	17/01/2005	20:09:51	5263.32
9	20/01/2005	07:42:16	20/01/2005	08:55:25	5937.36
10	07/09/2005	14:11:01	10/09/2005	02:37:32	951.42
11	13/09/2005	17:43:23	14/09/2005	07:52:09	48.30
12	05/12/2006	13:06:23	07/12/2006	17:41:55	1452.44
13	12/12/2006	20:10:55	13/12/2006	08:05:24	2018.04

3. Solar data and selected SPEs recorded by SREM

For the present SREM SPE analysis the following space instruments were used for Radio/Optical/X-ray (ROX) observations of solar flares:

1. The Reuven Ramaty High Energy Solar Spectroscopic Imager, RHESSI (Lin et al. 2002)
2. The Extreme ultraviolet Imaging Telescope (EIT) , the Large Angle and Spectrometric Coronagraph (LASCO) and the Charge, Element, and Isotope Analysis System/ Solar Extreme-Ultra-Violet Monitor (CELIAS/SEM) onboard the Solar and Heliospheric Observatory, SOHO, (Domingo et al. 1994, 1995)
3. The Transition Region and Coronal Explorer, TRACE (Handy et al. 1999)
4. The WAVES instrument onboard WIND satellite (Bougeret et al. 1995)
5. The Solar Optical Telescope (SOT), the X-ray Telescope (XRT) and the EUV Imaging Spectrometer (EIS) onboard HINODE satellite (Kosugi et al. 2007)
6. The X-ray Sensor (XRS) oboard GOES satellites

Table 2.: Association of SPEs with solar events (flares and CMEs). Only associations with major X-class solar flares are presented. Event numbers correspond to the selected SREM events presented in Table 1.

	Flare event				Coronal Mass Ejections		
Event	Peak (UT)	Flare class	Location	AR No	Onset (UT)	PA (degrees)	Speed (km/sec)
1	18:19	X1.2	N02W38	10484	17:54	270	1537
2	11:10	X17.		10486	11:30	Halo	2459
3	20:49	X10.	S15W02	10486	20:54	Halo	2029
4	17:25	X8.3	S14W56	10486	17:30	Halo	2598
5	19:50	X28	S19W83	10486	19:54	Halo	2657
6	00:43	X1.2	N14E08	10720			
7	23:02	X2.6	N14W08	10720	23:06	Halo	2861
8	09:52	X3.8	N15W25	10720	09:30	Halo	2094
9	07:01	X7.1	N14W61	10720	06:54	Halo	882
10	17:40	X17.	S11E77	10808			
	21:06	X5.4	S11E74	10808			
	03:00	X1.1	S12E68	10808			
	09:59	X3.6	S11E66	10808			
	20:04	X6.2	S10E58	10808	19:48	Halo	2257
	16:43	X1.1	S11E47	10808			
	22:11	X2.1	S13E47	10808	21:52	Halo	1893
11	19:27	X1.5	S09E10	10808	20:00	Halo	1866
	23:22	X1.7	S10E04	10808	23:36	170	999
	08:38	X1.1	S12W14	10808			
12	10:35	X9.0	S07E68	10930			
	18:47	X6.5	S06E63	10930			
13	02:40	X3.4	S06W23	10930	02:54	Halo	1774
	22:15	X1.5	S06W46	10930	22:30	Halo	1042

Available data corresponding to X class flare events that occurred during the selected for analysis time periods were downloaded and reduced using standard IDL Solarsoft routines or newly written IDL routines with emphasis given to the proper data reduction of two dimensional images (TRACE, SOHO/EIT).

SPE events that occurred during the periods of October-November 2003, January and September 2005 and December 2006 and were recorded by the SREM unit on-board INTEGRAL, which was closer to Earth and had a better defined orbit than ROSETTA with no data gaps like the PROBA SREM data records, were considered for this analysis. The selected SPEs are presented in Table 1.

4. Correlation of SPEs with solar events

For a correlation of SPEs with solar events the following facts have to considered:

1. Particles travel towards Earth along the interplanetary magnetic field (IMF)

2. The location on the surface of the Sun where the flare occurred affects both the intensity and the arrival time of high speed particles at the Earth

3. Particle fluxes originating from flares that occur in the center of the Sun's disc, have a completely different behavior than particle fluxes from flares occurring at the solar limb.

4. SPEs originating from the West limb are usually impulsive-like events, showing a fast intensity rise directly reflecting the flare profile, while SPEs originating from the East Limb and the center of the solar disc usually show a more gradual intensity increase

5. The arrival time for most energetic particles can vary from a couple of hours to almost a day (or sometimes even days) depending both on the location of the flare, the magnetic connectivity of the flare site to Earth and the energy (velocity) of the particles.

Taking into account the aforementioned facts and the information collected by all available ROX observations we have established correlations for all recorded SPEs with solar events which are shown in the following Table 2. Only associations with major X-class flares are presented in this Table.

5. Conclusions

The extensive analysis of solar data showed clear correlations with X class solar flares and CMEs for the events that occurred during October-November 2003, January 2005 and December 2006. For the September 2005 period correlations with X class flares and CMEs were possible but not straightforward due to the complexity of the registered SREM events.

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