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Proportionality law between the flare SXR intensity and the number of released solar near-relativistic electrons

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Abstract

We study a set of solar near-relativistic (NR; >50 keV) electron events observed by the *Wind* and the *ACE* spacecraft near the Earth orbit. Interplanetary transport simulations are used to take into account the propagation effects from the source to the spacecraft. Inversion methods developed within the EU/FP7 SEPServer project are then used to extract, from directional intensities observed near the Earth orbit, the electron release history in the low solar corona. We compare the release time histories with context electromagnetic observations of solar eruptions, in soft X-rays, radio, hard X-rays and white light.
The distribution of release profiles is bimodal. NR electrons are released during either short (<30 min) or long (>2 h) periods. Short release episodes appear to originate in solar flares, in coincidence with the timing of type III radio bursts reaching the local plasma line measured at 1 AU. The origin of long release episodes seems to be more intricate. They are associated with signatures of long acceleration processes in the low corona (long decay of the soft X-ray emission, type IV radio bursts, and time-extended microwave emission).
We present a proportionality empirical law between the intensity of the SXR flare and the number of electrons released during flare-accelerated events.

1 Introduction

Solar energetic particles (SEPs) observed in space represent a fundamental sample of the regions in which they were accelerated, and of the properties of the interplanetary medium through which they propagated. The SEP time-intensity profiles, the spectra and the anisotropies measured in-situ are a result of a combination of both source and transport effects. In some cases, the in-situ event represents an incomplete sample of the SEP population accelerated at the Sun, as a fraction does remain confined [1, 2], and those particles which are release into space have access to many coronal structures [3]. Open magnetic flux tubes can rapidly expand and cover several tens of degrees in longitude on the source surface. Some of these open field lines are found to connect the parent active region to the footpoint of the nominal Parker spiral, even when the parent active region is as far as 50° away [4].

The release time of the first arriving particles is inferred, in most observational studies, from either the dispersion in velocity observed during the event onset time [5] or by assuming that the first arriving electrons propagate scatter-free along an Archimedean interplanetary magnetic field line [6]. Two independent studies [5, 6] found that in many cases near-relativistic (NR; >50 keV) electrons were apparently released up to half an hour later than the solar type III radio burst. Only in few cases the inferred release time was consistent with the timing of the type III radio emission. The proposed explanations for these delays were attributed to other particle sources than solar flares, such as coronal shocks [5, 7], interplanetary transport effects not included in the approach [8], and observational problems related to pre-event background and cross-talk between energy channels [9, 10, 11, 12] that could mask the very onset of the event. In any case, a timing comparison between the apparent release time of the earliest electrons and the electromagnetic signatures of an event was proved to be inconclusive in many cases [3].

Modeling of the propagation of SEPs in the heliosphere is crucial to remove all the uncertainties inherent in the analysis of in-situ SEP observations. To unfold the SEP release time history from in-situ measurements, it is also necessary to take into account the angular response of the particle detector in the analysis of measured directional intensities [13, 14]. A systematic study of the timing and duration of the release processes of solar NR electrons was presented in [15]. They used in-situ measurements by both *ACE* and *Wind* spacecraft, and context electromagnetic observations in soft X-rays (SXRs), radio, hard X-rays (HXRs) and white light. They inferred the release time of the first arriving electrons by using both data-driven and simulation-based analysis methods.

In the present work, we review the methodology (Sect. 2) and the sample of flare-accelerated events in their sample (Sect. 3). In Sect. 4 we summarize the results and present a further analysis of the sample. Finally, Sect. 5 gives the conclusions of this work.

2 Methodology

Numerical simulations of the propagation of SEPs along the interplanetary magnetic field are a decisive tool to understand the sources of SEP events. It is currently possible to model their transport based on a good theoretical understanding of the processes that affect SEPs in the interplanetary medium [16, 17, 18, 19, 20].

The interplanetary transport models provides us with the response of the system to an impulsive (delta) injection at the Sun, which is the Green's function of particle transport. Particle intensities measured in the heliosphere as a function of time, energy, and direction are obtained as a temporal convolution of the source function (particle release profile) and the Green's function of particle transport at the spacecraft location. The sources of SEP events can be unfold by solving the inverse problem (deconvolving the in-situ measurements). Then one uses the measurements to infer the actual values of the model parameters. It is a

Table 1: Flare-accelerated events

Date	DOY	Solar Flare Start Time	Solar Flare X-ray Class	Released Part. (e sr^{-1} MeV^{-1})
1999 Jun 11	162	01:05	C1.0	6.8×10^{33}
2002 Feb 20	51	05:52	M5.1	1.1×10^{35}
		07:41	C2.5	
		09:46	M4.3	
2002 Dec 19	353	21:34	M2.7	3.4×10^{34}
		00:32	C4.5	
2004 Nov 1	306	06:14	B5.4	7.7×10^{34}
		06:55	C2.9	

deductive approach; it has the advantage that a systematic exploration of the parameters' space is possible, and the source function does not need to be parametrized a priori [13]. The problem is well constrained if one uses the observed directional intensities to compare with the simulation results. If the directional information in the data is scarce or one only uses the omni-directional intensities to fit the event, then the problem is ill-posed; that is, multiple combinations of source and transport scenarios can provide an explanation to the observational data [21].

SEPinversion is a software developed within the EU/FP7 project SEPServer[1] to infer the release time history and the interplanetary transport conditions of NR electrons. The software makes use of a database of simulation results [22] of an interplanetary transport model and it takes the detector response into consideration to unfold of the particle in-situ data. *SEPinversion* is IDL based and freely available online[2]. It is based on the work by [13].

3 Observations

We considered a sample of NR electron events observed during quiet interplanetary conditions. The sample consisted of 4 electron events observed by *Wind* [23] and *ACE* [24] in the energy range between 40 and 300 keV (0.4-0.7c). All the events showed a significant enhancement of NR electron intensities (i.e. a peak intensity at least an order of magnitude above the pre-event background in the 102–175 keV energy channel), and velocity dispersion at the onset of the event. In addition, the particle directional distributions were observed with good coverage. Table 1 shows a list of event dates and DOY in our sample.

Context electromagnetic observations of the parent solar activity were considered in [15]. They included SXR emission by the *GOES* satellite, HXR observations from *RHESSI* [25], whenever available, and white-light observations of CMEs reported in the *SOHO*/LASCO

[1] `http://wwww.sepserver.eu/`

[2] `http://server.sepserver.eu/`

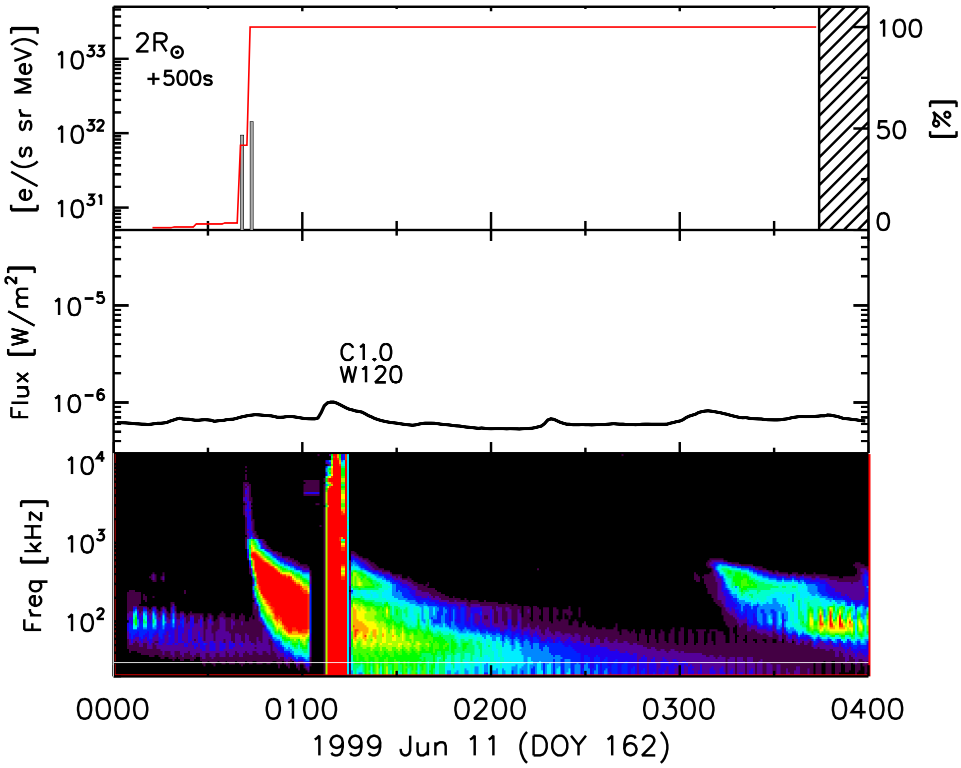

Figure 1: From top to bottom and for each event: (A) Electron source profile deduced at $2R_\odot$ (gray histogram) and total percentage of electrons (red curve; right axis). The profile has been shifted by +500 s to allow the comparison with the electromagnetic emissions. (B) SXR and HXR flux (red curve; right axis) when available. (C) Radio flux (the white horizontal line marks 30 kHz).

CME catalog [26]. Decametric-to-kilometric radio spectra by the WAVES experiment [27] on board the *Wind* spacecraft were considered. Table 1 summarizes the start time and the class of the associated solar flares in SXRs.

4 Results

The *SEPinversion* software was used in [15] to extract, from the directional intensities observed near 1 AU, the electron release history. The events listed in Table 1 showed a prompt release profile lasting less than 30 min. At low energies (50–82 keV or 62–102 keV, depending on the observations), the timing of the first particle release agrees with the timing of the type III radio burst within 5 min. Moreover the duration of the release is consistent with the duration of the main type III burst of the period. Figure 1 and Figure 2 show the results obtained for the events on 1999 June 11 and 2002 Feb 20, respectively.

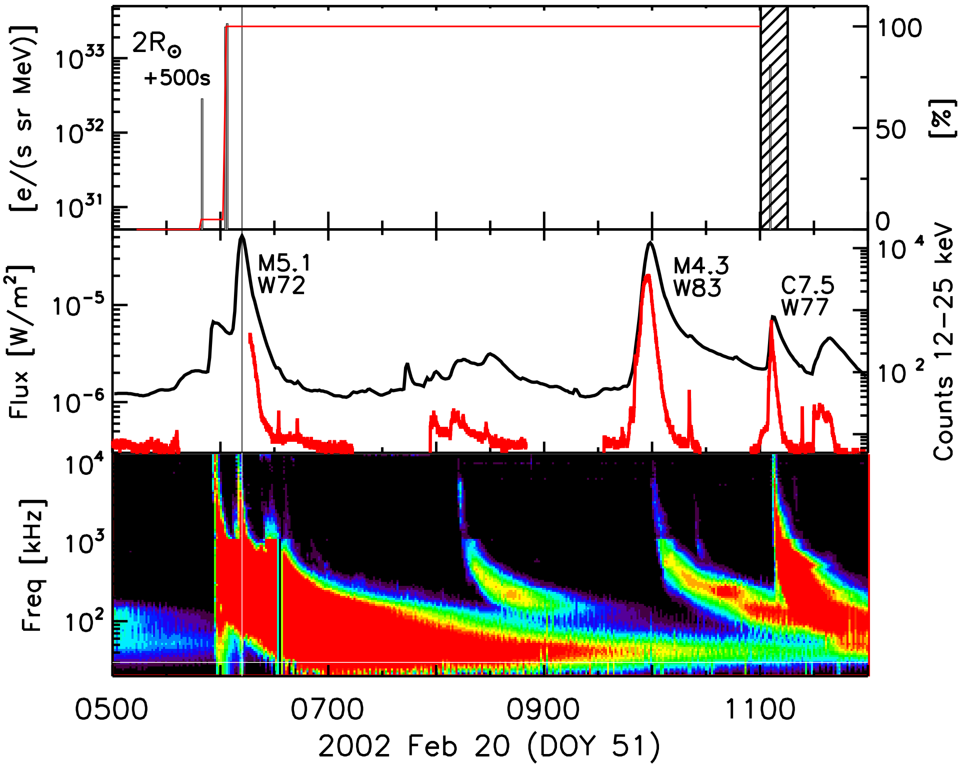

Figure 2: Same format as in Figure 1

For each event, the inferred amount of 62–102 keV electrons released in the interplanetary medium is shown in the last column of Table 1. The values range from $\sim 10^{33}$ to 10^{35} e sr^{-1} MeV^{-1}. The values were estimated both using *ACE* and *Wind* observations. For the same date, these values were consistent within a factor of 3.

Figure 3 shows the inferred number of released electrons as a function of the intensity of the associated SXR flare. The points inferred for the events in Table 1 are marked by crosses; the dots show the values inferred by [14].

Excluding the data points obtained for the 1999 Jun 11 and the 2004 Nov 1 events, we find a power-law fit between the number of released electrons during prompt periods (in e sr^{-1} MeV^{-1}) and the intensity of the SXR flares (in W m^{-2});

$$N_e = a(I_{SXR})^b \tag{1}$$

where we find $a = 37.4 \pm 0.4$ and $b = 0.56 \pm 0.09$ with $r = 0.924$.

The flares on 2004 Nov 1 and on 1999 Jun 11 were occulted behind the west limb. In both cases, the high-frequency part of the DH type III bursts was weak and no SXR counterpart was observed, suggesting activity rooted on the backside of the Sun. The degree of occultation seems larger for the 2004 Nov 1 flare because the weak high-frequency part of

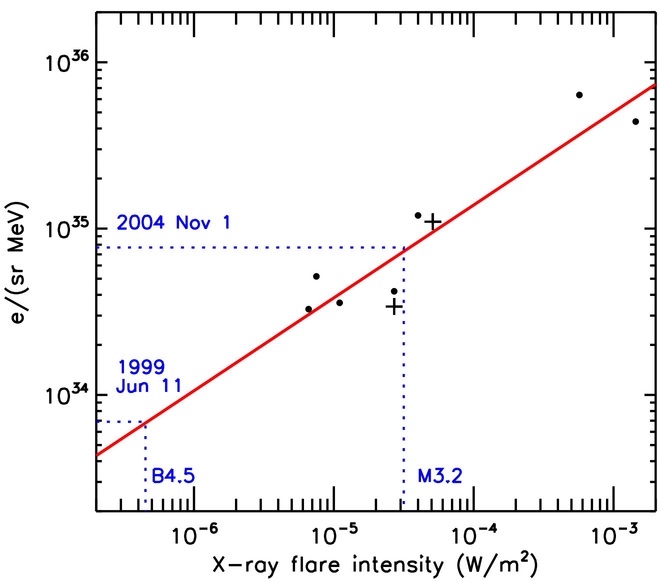

Figure 3: Number of released electrons in the 62-102 keV energy range versus the intensity of the associated SXR flare (crosses). Cicles show data from an earlier study by [14]. The blue dotted lines mark the SXR class of the 2004 Nov 1 and the 1999 Jun 11 flares, if they had not been occulted.

the radio spectrum extends to lower frequencies.

We use the empirical proportionality law to estimate the actual X-ray class of these flares. Given the inferred number of released electrons, the 1999 Jun 11 flare would correspond to a B4.5 flare while the 2004 Nov 1 flare would have a M3.2 class. In both cases, small SXR flares were reported after the beginning of the type III emission (25 and 51 min later) with X-ray classes C1.0 and B5.4, respectively. These have no ovious relationship with the occulted active regions. At least the 2004 Nov 1 B5.4 flare was observed in HXR coming from a different location ([940,200] arsec) than the previous HXR burst ([688,195] arsec), which occured in association with the type III radio burst.

5 Conclusions

Electron events associated with short release episodes appear to originate in solar flares. In addition to the correspondence found by [15] between the timing of the release and the observed type III radio bursts, we found a proportionality between the intensity of the SXR flare and the number of released electrons. The obtained proportionality law (with correlation coefficient 0.924) provides further support to the interpretation that these events were flare-accelerated.

The empirical law could be used in space weather studies to estimate the amount of particle radiation expected to be released in the heliosphere based on the solar flare intensity.

Also, the empirical law can be applied the other way around (like in this study), to estimate the flare intensity of solar flares rooted behind the solar limb, for which the SXR emission reaching the Earth is diminished.

Magnetic connectivity always plays an important role in relating the solar activity with a given point of the heliosphere. One should only expect an associated release episode onto the spacecraft magnetic field line when the associated type III radio burst is reaching the plasma line near the spacecraft.

Acknowledgments

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