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RADIO SIGNATURES OF SOLAR ENERGETIC PARTICLES DURING THE 23$^{\rm RD}$ SOLAR CYCLE

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Abstract. We present the association rates between solar energetic particles (SEPs) and the radio emission signatures in the corona and IP space during the entire solar cycle 23. We selected SEPs associated with X and M-class flares from the visible solar hemisphere. All SEP events are also accompanied by coronal mass ejections. Here, we focus on the correlation between the SEP events and the appearance of radio type II, III and IV bursts on dynamic spectra. For this we used the available radio data from ground-based stations and the Wind/WAVES spacecraft. The associations are presented separately for SEP events accompanying activity in the eastern and western solar hemisphere. We find the highest association rate of SEP events to be with type III bursts, followed by types II and IV. Whereas for types III and IV no longitudinal dependence is noticed, these is a tendency for a higher SEP-association rate with type II bursts in the eastern hemisphere. A comparison with reports from previous studies is briefly discussed.

Key words: Solar energetic particles - radio bursts - solar cycle 23

1. Introduction

Solar energetic particle (SEP) events are transient flux enhancements of electrons, protons and ions due to acceleration processes in the solar corona and interplanetary (IP) space. The high energy particles can pose a serious risk for the near Earth and ground-based technological devices, may disturb communications and be a health hazard (Mewaldt, 2006). This is why energetic particles are of major space weather interest. The accelerator of these particles, however, is still a subject of debate. Presently, the reconnection processes during flares (Cane *et al.*, 2002) and the shock-acceleration at coronal mass ejections (CMEs), Reames (1999), are recognized as efficient particle accelerators. An important issue is whether both acceleration processes act simultaneously with comparable efficiency or one of them dominates the particle energization process. In the current two-class SEP picture, the flares are thought to dominate the *impulsive* events and the shock waves dominate the large *gradual* events. Observations, however, are not able to relate unambiguously the SEP parameters measured in situ to the parent solar activity (e.g., flares vs. shocks). The large uncertainties usually present when doing different correlation analyses may arise due to the poorly known particle transport in the turbulent IP magnetic field, the magnetic connection between the acceleration site and the Earth, and that SEPs are often just measured at a single point in space.

Radio observations can provide additional information and constraints for identifying the particle accelerator in the corona and IP space. When nonthermal electrons propagate through the solar corona they may emit radio waves, if certain conditions apply (Nindos *et al.*, 2008). The different types of radio bursts in the dynamic radio spectrum (see e.g., a review by Pick and Vilmer (2008)), are usually interpreted as signatures from electrons accelerated in the vicinity of a shock wave (type IIs), as electron beams (type IIIs) or as electrons confined in closed loop structure during the early evolution of a CME (type IVs). Type III bursts usually extend to low frequencies (reaching as far as the Earth orbit, $\sim$20 kHz) which is the main indicator that accelerated electrons (and by inference also protons) can efficiently escape from the solar corona (Cane *et al.*, 2002). Interplanetary counterparts of type II are also observed, but to lesser extent, whereas type IVs can be seen only to few MHz, but not to lower frequencies. Here we focus on the comparison of the particle (mainly proton) intensities measured in situ with the electromagnetic emission of electrons in the corona and IP space over the entire solar cycle 23.

Numerous previous studies reported different association rates of SEPs and emission of radio bursts of type II (Cliver *et al.*, 2004; Gopalswamy *et al.*, 2008), III (Cane *et al.*, 2002) and IV (Kahler, 1982). The aim here is to identify the different types of radio emission from the dynamic spectra, to complement our results with reports from the different radio observatories and to compare them with previous works on the topic.

2. Particle data

In the present work we selected all proton events with energy above 25 MeV as identified by Cane *et al.* (2010) that are associated with both strong flares (X and M-class) at eastern and western heliolongitudes and CMEs. Here we will differentiate the SEP events into eastern/western only and not by other SEP classifications schemes (Reames, 1999; Cliver, 2009), since any classification may leave out many 'mixed' cases in abundances, charge states, associated phenomena, etc. However, in order to facilitate comparison with previous work, we note if the SEP event was described as 'gradual' or 'impulsive' in Reames and Ng (2004) and Cliver and Ling (2009) by the superscripts 'g' and 'i', respectively.

In order to improve the statistics for the radio analysis (see next Section) we included SEP events that have high background level due to a previous event[1], that are observed during SOHO data gap, those for which no value for the peak intensity was given due to instrument saturation (with superscript 's') and those with parent activity at the limb (with superscript 'l' we denote events at the solar limb and with 'c', events close to the disc center, between ± 10 degrees in heliolongitude). That lead finally to 175 particle events during solar cycle 23, of which 49 had sources in the eastern hemisphere, 124 in the western and two had uncertain source locations.

3. Radio spectrograph data

The radio emission observed on ground and in space is usually presented in a frequency vs. time plot, where the strength of the radio emission is color-coded. This is known as a dynamic radio spectrum. Several features were recognized on such spectrum plots, e.g., fast drifting emission stripes extending from high to low frequencies (type IIIs); slowly drifting lanes of emission (type IIs) and a broad band stationary or/and drifting emission of type IV. Each of these radio emission types is a result of a unstable electron population (produced by a different process) generating Langmuir

[1]Several events with high background are not present in the list of Cane *et al.* (2010) but are adopted from Klein *et al.* (2011), noted with superscript 'n'.

Table I: List of radio data sources

Observatory	Frequency range	Data link
Phoenix-2	100−4000 MHz	http://soleil.i4ds.ch/solarradio/
HiRAS	25−2500 MHz	http://sunbase.nict.go.jp/solar/denpa/index.html
Culgoora	18−1800 MHz	http://www.ips.gov.au/World_Data_Centre/1/9
Ondrejov	800−4500 MHz	http://www.asu.cas.cz/~radio/info.htm
Potsdam	40−800 MHz	http://ooo.aip.de/groups/osra/data/montab/
Artemis	20−650 MHz	http://web.cc.uoa.gr/~artemis/Artemis4_list.html
Izmiran	25−270 MHz	http://www.izmiran.ru/stp/lars/
Learmonth	18−180 MHz	http://www.ips.gov.au/World_Data_Centre/1/9
RSTN	18−180 MHz	ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_RADIO
DAM	20−75 MHz	http://bass2000.obspm.fr/home.php
Green Banks	18−70, 170−1070 MHz	http://www.astro.umd.edu/~white/gb/index.shtml
Wind/WAVES	0.02−14 MHz	http://www-lep.gsfc.nasa.gov/waves/data_products.html

waves that convert into electromagnetic radiation via wave-wave processes. Namely, type IIs are usually assumed to be the shock signatures in the corona/IP space (Nelson and Melrose, 1985), type IIIs are electron beams propagating through the corona (Suzuki and Dulk, 1985), and the type IVs are the signatures from trapped electrons in coronal loops (Stewart, 1985; Pick, 1986). Here, we will use this standard interpretation for the radio burst emission in order to identify the probable particle accelerator. As a preparatory work for the analysis we collected all available radio spectral data (summarized in Table I) and the associated GOES soft X-ray (SXR) emission for each SEP event. The results of the associated radio bursts to each particle event are summarized in Tables II and III. There, we start with the SEP event date followed by the onset (in UT) of the SXR emission associated with each event as provided by GOES satellite (1−8 Å channel).

The so-identified radio emissions of type II, III and IV are organized in several frequency (wavelength) ranges in Tables II and III. Namely, the decimeter (dm) range is subdivided into high (0.8−3 GHz) and lower (0.3−0.8 GHz) frequency parts. Similarly, we divided the metric (m) range into 100−300 and 30−100 MHz subbands. The IP space (dekameter/hectometer, DH, and kilometer wavelengths) is represented by one column. The radio bursts were ordered by their type and not by their temporal appearance on the radio spectral plot.

Since we primarily used quicklook radio spectral data where image quality may be low, we also collected all available radio observatory reports for each event. In case radio emission of a given type was reported but could not be identified by us (due to low resolution of the actual image or because no radio spectrum plot was found), we give the result in squared brackets in Tables II and III. Any uncertain radio burst identification is indicated by a question mark following the roman number of the corresponding radio burst type. Weak emission signatures are denoted with superscript 'w', delayed emission with 'd' and low (high)-frequency emission onset with 'LFo' ('HFo'). Unclassified emission is given with 'UNCLF', fine structures with 'FS' and fundamental-harmonic emission with 'FH'. Continuum ('CONT') and decimeter ('DCIM') emission in the 0.3−3 GHz range is considered as type IV-like emission in the analysis. The complete particle event list together with the associated radio bursts is given in Tables II and III (for western and eastern events, respectively).

4. Results

The results are given as normalized number of the SEP events vs. radio frequency for each wavelength range (dm, m and DH), see the histograms on Figure 1, for eastern (on the left) and western (right) SEP events. The numerical value of the association rates, graphically presented on the histograms, is given by the height of each color bar. The SEP events associated with specific burst types as identified on the radio spectral plots are given with black color. With dark gray is shown the association in cases where the burst type was only given in the observatory reports (no spectra found at present) or where its identification is questionable. Whenever we give a value for an association rate, we will always sum up these two sections. Finally, with light gray color we denote the number of SEP events for which no radio information could be found (neither plots nor observatory reports). The majority of the missing radio plots is in the dm-range due to poor data coverage. Note that the highest discrepancy between the results given by us and by observatory reports is for the type II burst identification in the DH-range. This is mostly due to the weak and intermittent appearance of the IP type II bursts which makes an identification on quick-look plots difficult. In addition, the subjectivity of the observer plays a prominent role here, whereas the DH-type III identification, for example, is straightforward.

On the histograms, the number of events in each column is normalized to the total number of events in each group (eastern and western, correspondingly) and is also given explicitly in Table IV. While representing the association rate in the dm and m-range, we chose the greater association rate among their two subbands. For the total number of SEP events, given

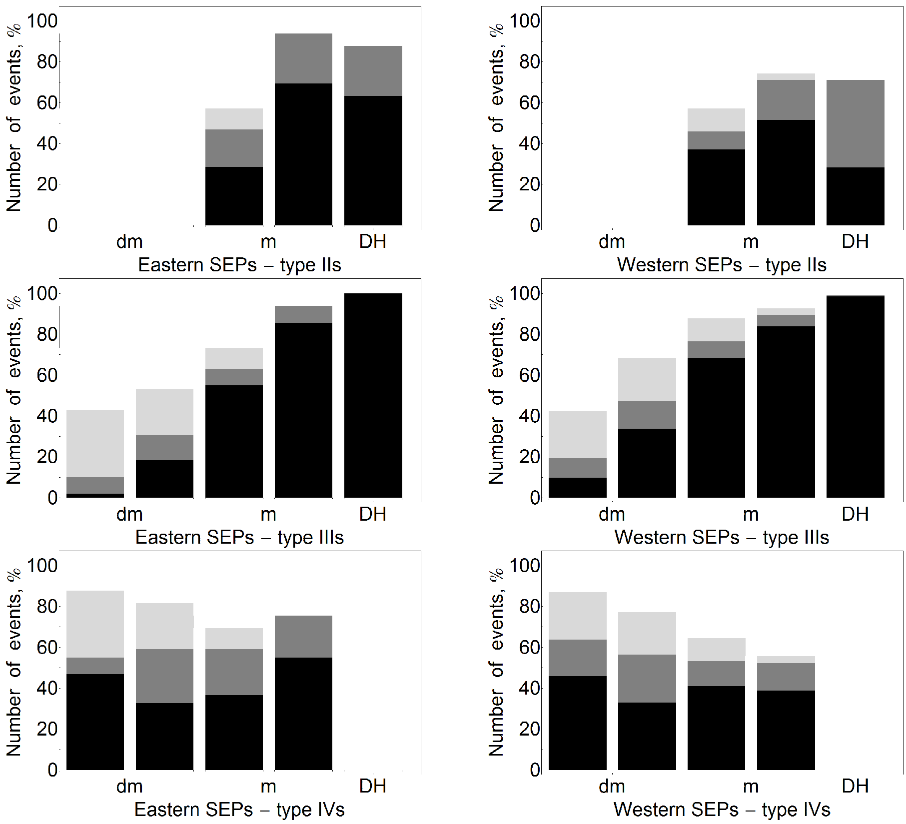

Figure 1: Histograms of the association rates of eastern (lest) and western (right) SEP events and the corresponding radio burst types for dm (3–0.8 and 0.8–0.3 GHz), m (300–100 and 100–30 MHz) and DH (30–0.02 MHz) range. For the color-code see text.

with 'All' in Table IV, we sum up the eastern, western and the uncertain SEP events. Since the dm-type II burst and the DH-type IV bursts are intrinsically rare phenomena, they will be excluded from the further analysis.

The highest association rate of SEPs is with the m and DH-type III bursts, usually $\gtrsim 90\%$ (see Table IV for details). A much lower association rate between SEPs and type IIIs is found in the dm-range (from about 30 to 50%). No dependence on the eastern vs. western heliolongitudes is seen for type III and type IV bursts, with the association rate of the type IV bursts being in the range from 50% up to 75%. In contrast, the SEP-association rate with the 30–100 MHz metric (94%) and the DH type II bursts (88%)

is slightly higher for eastern SEP events than for western ones (71 %).

5. Discussion

We present the association rates of the SEP events (protons) and their accompanying radio emission (from electrons) in the corona (dm and m wavelength) and IP space (DH-range). Since there are no signatures of protons interacting with the solar atmosphere (with the exception of gamma-ray emission), we use electron signatures as a diagnostic for particle acceleration from the corona up to 1 AU.

Cane *et al.* (2002) were the first to identify long-lasting groups of DH type III bursts as a typical radio counterpart of large SEP events. They found the groups to be of significantly longer duration than type III bursts associated with impulsive flares, see also MacDowall *et al.* (1987). In the analysis performed here, we did not take into account the burst duration of DH-type III, nor explicitly separate the SEP events into gradual or impulsive. Still we find that SEP events have the highest association rate with type III radio bursts. This implies that the electrons accelerated in the corona (within one solar radius) have a ready access to the IP space, irrespective of whether the SEP event is impulsive or gradual.

Shock signatures (type II bursts) were also considered in correlation studies with SEP events. We found a lower association rate (up to 75%) of the DH-type II bursts with SEP events, compared to the m- and DH-type III association rates. The number increases when only SEP events with strong intensities are considered, in agreement with Gopalswamy *et al.* (2002) and Cliver *et al.* (2004).

The association of SEP events with types III and IV is comparable in the eastern and western groups (see Figure 1). But for the type II bursts there is a slight trend for a higher association rate in the eastern hemisphere. This result could be understood it terms of different sources contributing to SEP events. Shocks could be the dominant accelerator when the parent activity is poorly connected to Earth (as in the eastern solar hemisphere). In the western hemisphere (where more than twice as many events were detected) both flare and shock acceleration could contribute. When no shock signatures accompany the eastern SEP events, their propagation through the IP space and detection at Earth could be facilitated by a large-scale magnetic structure, e.g., interplanetary coronal mass ejections (ICMEs). Richardson *et al.*

(1991) estimated that for about 15% of the eastern events this is likely the case. Recently Miteva *et al.* (2013) showed similar occurrence rate of ICMEs for the western SEP events (20%).

The association with the type IIIs seems to be increasing with the decreasing of the radio frequency (from dm to DH-range). At first, the type III identification in the dm-range might be masked due to overlying decimeter continuum often present in the dynamic radio spectra (observational bias). Hence, the obtained association rates of dm-IIIs are to be considered as lower limits only. In addition, high frequencies and dense plasma impede the production and growth of Langmuir waves. Also, the electron beam must travel an 'instability distance' from the acceleration site before Langmuir waves are generated (Reid *et al.*, 2011). This can cause a lack of high frequency type III emission in even the most energetic of electron beams. Moreover, collisions of both waves and electrons can suppress Langmuir wave growth at high frequencies, e.g., Kane *et al.* (1982); Reid and Kontar (2012).

Without the intention to give a complete overview on the results from previous work, we selected few statistical studies that are (partially) covering solar cycle 23. The different association rates are given in Table IV and are mostly consistent, although in many earlier studies only large SEP events were considered.

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Table II: Solar energetic particle events with origin at western heliolongitudes: visual identification and [observatory reports] of type II, III and IV radio bursts.

Event	SXR	dm-λ		m-λ		DH-λ
yymmdd	onset	3−0.8 GHz	0.8−0.3 GHz	300−100 MHz	100−30 MHz	30−0.02 MHz
970521	20:08	III?	III?, IV	III, IV	II^{FH}, III, IV	II^{FH}, III
971103	10:18	DCIM	III, IV^{FS}	II^{FH}, III, IV	II^{FH}, III, IV	II^{FH}, III
971104	05:52	III	III	II^{FH}, III, IV	II^{FH}, III, IV	[II], III
971106[g]	11:49	CONT	III, IV	II, III, IV	II?, III, IV	II?, III
980502	13:31	DCIM	III, IV	II?, III, IV	II, III, IV	II, III, IV
980506	07:58	DCIM	III, IV	II^{FH}, III, IV	II, III	II, III
980930[g]	13:08	DCIM	CONT	[II], III	[II], III	[II], III
981105[g]	19:00	no data	no data	III, IV	[II], IV	[II], III
981122	06:30	UNCLF	III	[II], III	[II], III	III
981122[n]	16:30	no data	no data	no data	no data	III
981217	07:40	[DCIM]	III	II, III	II, III	III
990604[g]	06:52	DCIM	DCIM, [III]	CONT	II^{FH}, III	II^{FH}, III^{w}, [IV]
990627	08:34	[DCIM]	[DCIM, III]	III	II, III	III, [IV]
990828	17:52	no data	no data	no data	[II, III]	[II], III
991228	00:39	CONT	III, IV?	II^{FH}, III	II^{FH}, III	III
000212	03:51	[DCIM]	IV	IV	II, III, IV	II?, III
000302	08:20	DCIM, [III]	CONT?	II^{FH}, III	II^{FH}, III, IV	II^{FH}, III
000303	02:08	III	III	II^{FH}, III, IV	II^{FH}, III, IV	III
000322	18:34	no data	no data	no data	[II, IV]	III^{d}
000324	07:41	DCIM	CONT	II, III	II, III	[II], III
000404[g]	15:12	DCIM	III, IV	II, III, IV	II, III	[II], III
000501[i]	10:16	DCIM	no data	III	III	III^{w}
000523[i]	20:48	no data	no data	III	III	III
000610	16:40	[DCIM]	no data	no data	[II, III]	[II], III
000615	19:38	no data	no data	no data	[II]	[II^{FH}], III
000617	02:25	IV?^{d}	III^{d}	III^{d}	III	[II], III^{LFo}, [IV]
000618	01:52	CONT?	CONT?	II^{HFo}, III	II, III	III
000623	14:18	DCIM	[DCIM]	[DCIM]	II, IV	II, III
000625	07:17	no data	[DCIM]	II?^{w} , IV	II, [IV]	[II^{w}], III^{w}
000714[c,g]	10:03	DCIM	no data	II?, III, IV?	III	[II], III
000722	11:17	DCIM	[IV]	II^{FH}, III, [IV]	II?, III, IV	[II], III
000812[i]	09:45	DCIM	[III]	[III]	II?, III?	III^{w}
000909	08:28	DCIM, II?	II?, [III], IV?	II^{FH}, III	II^{FH}	III^{w}
000912[c]	11:31	no data	no data	II^{FH}, III	II, III^{d}	II, III
000919	08:06	DCIM	[II^{HFo}], III, IV?	II, III, IV	II, III, IV	II?, III
001108[g,s]	22:42	[IV]	[IV]	[III, IV]	III, [IV]	II, III
001124[c,g]	04:55	III	III	II, III	II, III	II, III
001124[c]	14:51	[DCIM, III]	[DCIM, III]	II, III	II, III	II, III
010128[g]	15:40	no data	no data	no data	no data	[II], III^{w}
010310	04:00	III	III	II, III	II, III	[II^{w}], III
010329	09:57	DCIM, [III]	IV	II, III, IV	II, III, IV	II?, III
010402	10:58	DCIM	III?	III, IV	II^{FH}, IV	II, III^{w}
010402	21:32	IV	III, IV	II, III, IV	II^{FH}, III	II, III
010409[c]	15:20	[DCIM]	IV	II^{FH}, III, IV	II^{FH}, III, IV	II, III
010410[c,g]	05:06	[IV]	III, IV	III, IV	II, III, IV	[II], III
010412	09:39	DCIM	IV	II^{FH}, IV	II, III, IV	II?, III
010414[i]	17:15	no data	no data	[III]	[II, III]	III
010415	13:19	DCIM	[IV]	[IV]	[II, III, IV]	II^{FH}, III
010426	11:26	DCIM	no data	no data	no data	II?, III^{w}
010719	09:52	DCIM	no data	III^{w}	III^{w}	III^{w}
010912	21:05	no data	III	III	[II]	III^{w}
010915	11:04	no data	no?	III	III, IV?	II^{FH}, III^{w}
011019	00:47	IV	IV	II, III, IV	II, III	II^{FH}, III
011019	16:13	no data	no data	II, III, IV	II, III, IV	II^{FH}, III
011022	00:22	III?	III	III	III	III
011025[n]	14:42	[DCIM]	[II, IV]	[II, IV]	[II], III?, IV	II^{FH}, III^{LHo}
011104[g]	16:03	no data	no data	II, III, IV	II, III, IV	II, III
011122[g]	20:18	IV^{d}	bad quality	II, III	II, III	[II], III
011122	22:32	III, IV	III, IV	III, IV	III, IV	[II], III
011226[g]	04:32	IV^{d}	IV	III, IV	II, III, IV	II^{FH}, III

Table II: cont'd

Event	SXR	dm-λ		m-λ		DH-λ
yymmdd	onset	3−0.8 GHz	0.8−0.3 GHz	300−100 MHz	100−30 MHz	30−0.02 MHz
020220	05:52	III	III	II, III	II^{FH}, III	III
020315[c]	22:09	IV^{FS}	[IV]	III, IV	III^{w}, [IV]	[II^{FH}], III^{LFo}
020411	16:16	DCIM	[DCIM]	[III]	[III]	[II, III]
020414	07:28	[DCIM, III]	[DCIM, II], III	III	[II], III	II, III
020415[s]	02:46	UNCLF	CONT?	III, CONT?	III	II, III
020417	07:46	DCIM, [III]	[II], III?, IV	[II], III, IV	II, III, IV	II?, III, IV
020421[g]	00:43	IV	III, IV	II?, III, IV	II^{FH}, III	[II], III
020715[c]	19:59	IV^{FH}	III	III, IV	III, IV	[II], III
020803[i]	18:59	no data	no data	III	III	II^{FH}, III
020814[g,l]	01:47	UNCLF	UNCLF	II^{FH}, III	II^{FH}, III	[II], III
020816	05:46	[DCIM]	DCIM, [II^{HFo}], III	II^{FH}, III	II, III	II, III^{w}
020818[i]	21:12	no data	III	III	II, III, IV	III, IV^{d}?
020819[i]	10:28	DCIM, [III]	III	III	III	III
020820[i]	08:22	DCIM	III	III	III	III
020822	01:47	CONT	III	III, IV	II, III, IV	III
020824[g]	00:49	III?	III^{d}	II^{FH}, III	III, [IV]	II^{FH}, III
021109[g]	13:08	DCIM	[IV]	[IV]	II, III, [IV]	II?, III
021219[c]	21:34	no data	no?	[III, IV]	II, III, IV	II?, III
021222	02:14	IV^{d}?	III?	III?	II^{FH}, III	III
030317	18:50	no data	no data	III	III	III
030318	11:51	DCIM	[II, IV]	[II, IV]	II, III	[II], III
030423	00:39	IV^{FH}	III, IV	II^{FH}, III, IV	II, III, IV?	III
030424	12:45	DCIM	[II], III, [IV]	[II], III, [IV]	[II], III, IV	III^{w}
030527	22:56	III, IV	IV	II^{FH}, III, IV	II?, III	[II], III
030528	00:17	IV	III, IV	III, IV	III, IV	[II], III, [IV]
030531	02:13	IV	III, IV	II^{FH}, III	II^{FH}, III	II?, III
030819	07:38	DCIM	[DCIM]	II^{FH}, III, IV	II^{FH}, III, IV	III
031026	17:21	no data	no data	no data	II?, III, CONT?	II?, III
031029[c]	20:37	IV	III, IV	II^{FH}, III, IV	II^{FH}, III, IV	II?, III, IV
031102	17:03	[DCIM]	no data	no data	no data	II^{FH}, III, [IV]
031103[n]	01:09	UNCLF	IV	[II], III, IV	[II], III, [IV]	[II], III
031103[n]	09:43	DCIM	DCIM, [II^{HFo}], III?	II, III, IV	II, III, IV	II^{FH}, III, [IV]
031104	19:29	III, IV^{d}	III, IV^{d}	II^{FH}, III, IV	II, III, IV	II?, III
031120[c]	07:35	DCIM?	III^{w}?	III^{w}?	III, IV?	III
040204	11:12	DCIM	III, IV	II^{FH}, III, IV	III, IV	III^{w}
040411	03:54	no?	III	III	III	[II], III
040713	00:09	III	III	II, III	II, III	II?, III
040725	14:19	DCIM	CONT?, III?	III?, CONT?	[II], III, IV	II?, III, IV
040919	16:46	no data	no data	no data	II, III, [IV]	[II], III
041030	06:08	III	III	II, III	II, III	III
041030	11:38	DCIM	[DCIM], III	II, III, IV	II, III, IV	III
041030	16:18	no data	no data	no data	II?, III	III
041107	15:42	[DCIM]	no data	no data	III, IV	II^{FH}, III, [IV]
041109	16:59	no data	no data	no data	II, III, IV	[II], III, [IV]
041110	01:59	III, IV^{FS}	III, IV	II^{FH}, III, IV	II, III	II?, III, IV?
050115[c]	22:25	no data	IV	IV	[II], III, IV	II, III, IV
050117	06:59	no data	IV	III, IV	III, IV	II, III, [IV]
050119[n]	08:03	[DCIM]	[DCIM]	II, III, IV	II, III, IV	[II], III^{w}, [IV]
050120	06:36	no data	[III], IV	III, IV	II, III, IV	II, III
050506	03:05	III	III	III	III	III
050506	11:11	DCIM, III?	[DCIM], III?	III	III, IV?	III
050511	19:22	no data	no data	no data	II? III	II?, III, [IV]
050616	20:01	no data	no data	III	[II], III, [IV]	[II], III
050709	21:47	no data	IV	III, IV	II, III, IV	II, III
050712	15:47	III?, DCIM	III?, DCIM	III?, [IV]	III, [IV]	III
050713	02:35	IV?	IV?	[III], IV?	III^{w}	III^{LFo}
050713	14:01	DCIM	IV?	IV?	III	[II], III
050714[l]	10:16	[DCIM], III?	[DCIM], III?	III, IV	III^{w}, [IV]	II, III^{LFo}
050822	00:44	IV^{d}	IV^{d}	II, IV^{d}	II, III, IV	II, III, [IV^{w}]
050822	16:46	[IV]	III?, IV?	III, IV	III, IV	II?, III
050915[n]	08:30	DCIM	CONT	no?	no?	no?
060706	08:13	[DCIM]	II?, IV	II, IV	II, III, IV	II?, III
061213	02:14	DCIM	IV	II^{FH}, III, IV	II^{FH}, III, IV	II?, III, [IV]
061214	21:07	no data	IV	IV	II^{FH}, III, IV	[II], III, IV?

Table III: Solar energetic particle events with origin at eastern or uncertain (with superscript 'u') heliolongitudes: visual identification and [observatory reports] of type II, III and IV radio bursts.

Event	SXR	dm-λ		m-λ		DH-λ
yymmdd	onset	3−0.8 GHz	0.8−0.3 GHz	300−100 MHz	100−30 MHz	30−0.02 MHz
970401	13:43	DCIM	[IV]	[IV]	[II], III, [IV]	II, III
970924	02:43	UNCLF	CONT?	III	II, III	III
980429	16:06	DCIM	IV	III, IV	II, III, IV	II?, III, IV?
980818^{l}	22:10	UNCLF	UNCLF	II, III	II, III, [IV]	II, III^{w}, IV?
980819	21:35	UNCLF	UNCLF	II, III	II, III, [IV]	II?, III^{w}, IV?
980824^{c,g}	21:50	IV?	III?, IV?	II, III, [IV]	II^{FH}, III, [IV]	II^{FH}, III
980920	02:33	no?	no?	III	II, III, IV	[II], III
980923^{c,g}	06:40	DCIM	IV	II, IV	II, IV	II, III
990503^{g}	05:36	DCIM	IV	IV	II, III, IV	II^{FH}, III
990629^{c}	05:01	no?	[DCIM, III]	[DCIM], III	II, III	II, III
991117	09:47	DCIM	no?	no?	III	II^{FH}, III
000118	17:07	no data	no data	no data	[II, III, IV]	[II], III
000217^{c}	20:17	no data	no?	II	II, III	II^{FH}, III
000510	19:26	no data	no?	UNCLF	II, III, IV	III
000606^{g}	14:58	DCIM	[II^{HFo}, III]	[II, III]	II, III, IV	II^{FH}, III
000710	21:05	no data	CONT	IV	II, III, IV	II, III, [IV]
001029	01:28	no data	IV	IV	II, III, IV	II, III
001125^{s}	00:59	no data	IV	IV	II, III, IV	II?, III
010120	18:33	no data	no data	II, III	II, III	II^{FH}, III
010325	16:25	[III, IV]	no data	no data	IV?	III
010615	10:01	DCIM	[DCIM]	[DCIM, II], III	III, IV	[II^{FH,w}], III
010917^{c}	08:18	DCIM	no data	II, III	II, III	II, III
010924^{g}	09:32	DCIM	no data	III, IV	II^{FH}, III, IV	II, III
011009	10:46	DCIM	no data	IV?	II, III, IV	II, III
011022	14:27	[DCIM]	[IV]	[III]	II, III, IV	II, III
011117^{g}	04:49	no data	IV	III, IV	II, III, IV	II?, III
011128	16:26	no data	no data	no data	II, III, IV	II?, III
020520	15:21	DCIM, III	[II], III, [IV]	[II, III, IV]	[II, III, IV]	III
020816	11:32	DCIM	[II^{HFo}], III, IV	[II], III, IV	II?, III, IV	II, III, IV
030421^{c}	12:54	III?, DCIM	III?, [IV]	II, III, IV	II, III, IV	III, IV?
030425	05:23	[III]	[III]	II, III	II, III	II, III
030615	23:25	no data	III, IV?	II, III, IV	II, III, IV	II, III
030717	08:17	DCIM	III	II, III	II, III	II?, III
031026	05:57	DCIM	IV	[II], III, IV	II, III, IV	II, III, IV?
031028^{c}	09:51	DCIM, [III]	[II], III, IV	[II] III, IV	II, III, IV	II, III, IV
031118	07:23	DCIM	[II^{HFo}], III, IV	II, III, [IV]	II, III, IV	II^{w}, III, [IV]
040107	10:14	DCIM	[IV]	II, III, [IV]	II^{FH}, III	II^{FH}, III
040912	00:04	no data	IV	III, IV	II^{FH}, III, IV	II?, III
041104	22:53	no data	III, IV	III, IV	[II], III, IV	II?, III, IV?
041202^{c}	23:44	IV	IV	IV	II, III, IV	II, III
050114^{c}	10:08	DCIM	[DCIM], III	III, IV	[II], III, IV	III
050115^{c}	05:54	IV?	IV	IV	II, III, IV	II, III, IV
050513	16:13	DCIM	III?, [IV]	[II, IV]	[II, III, IV]	II?, III, IV?
050603^{l}	11:51	DCIM	IV	[III]	[II, III]	II, III
050907^{l}	17:17	no data	no data	no data	[II, IV]	II, III
050913	19:19	no data	no data	no data	[II], III, IV	II, III, IV
061106^{l}	17:43	no data	no data	[II], III	[II], III	II, III
061205	10:18	DCIM	[DCIM], III	[DCIM], II, III	II, III	II, III
061206	18:29	no data	no data	[II], III, [IV]	[II], III, [IV]	II, III
980909^{u}	04:52	no?	no?	II, III	II, III	III
990216^{u}	02:49	CONT	CONT	II?, IV?	[II], III	III

Table IV: Association rates of SEP events and solar radio bursts.

SEP category	Association rates, % m-II	DH-II	dm-III	m-III	DH-III	dm-IV	m-IV	Reference	Time coverage	Number of events
				SEP events − radio bursts						
Eastern	94	88	31	94	100	59	75	this work	1997−2006	49
Western	71	71	48	89	99	64	53	this work	1997−2006	124
		90^{sr}						Cliver and Ling (2007)	1997−2003	140
All	78	75	42	91	98	61	58	this work	1997−2006	175
	82 ($88^{s}/80^{w}$)	63 ($96^{s}/50^{w}$)						Cliver *et al.* (2004)	1996−2001	88 ($24^{s}/64^{w}$)
	$90^{f,m}$	100^{m}						Gopalswamy (2003)	1997−2001	48
				100^{l}				Cane *et al.* (2002)	1997−2001	123
					$91^{l,m}$			MacDowall *et al.* (2003)	1997−2001	47
							88	Kahler (1982)	1973−1980	52
				Radio bursts − SEP events						
Eastern	$8^{yN}/52^{yY}$							Cliver *et al.* (2004)	1996−2001	50/23
Western	$25^{yN}/90^{yY}$							Cliver *et al.* (2004)	1996−2001	69/29
All	$61^{yY}/52^{nY}/30^{yN}$							Gopalswamy *et al.* (2008)	1996−2005	165/69/26

s (w): strong (weak) SEP event with peak intensity of $\geq (<)\, 0.1$ cm^{-2}s^{-1}MeV^{-1}sr^{-1}; sr: stronger SEP peak flux, > 10 MeV protons of $3 \sim 10^4$ cm^{-2}s^{-1}sr^{-1}; f: frontsided source location; l: long-lasting type III emission; m: major SEP event, > 10 MeV protons of ≥ 10 cm^{-2}s^{-1}MeV^{-1}sr^{-1}; yN: m but no DH-IIs; yY: m and DH-IIs; nY: no m but DH-IIs.