

A Search for Solar Energetic Particle Events with CME-less Flares

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Abstract. Solar energetic particle (SEP) events are associated both with flares and coronal mass ejections (CMEs). There have been many attempts to identify the origin of SEP through statistical correlations. But correlations of peak SEP intensities with CME speed or soft X-ray flare intensity are in general quite noisy. This motivates the research for SEPs that accompany ‘pure’ events, either CMEs or flares. We searched for SEP signatures of CME-less flares. Wang and Zhang (2007, ApJ 665, 1428) showed that about 10% of GOES X-class flares between 1996 and 2004 had no accompanying CME. Four occurred in the western solar hemisphere. We find that although they were accompanied by signatures of electron acceleration to relativistic energies in the corona (microwaves, hard X-rays), none displayed radio signatures of particle escape to interplanetary space (metric-to-kilometric type III bursts), and none produced an SEP event seen by GOES. This suggests that the accelerated particles remained confined in closed coronal magnetic structures.

Keywords: energetic particles, solar flares, coronal mass ejections

I. INTRODUCTION

Transient flux enhancements of solar energetic particles (SEPs) in space can be ascribed to acceleration in solar flares or at the bow shocks of fast coronal mass ejections (CMEs). From a purely statistical viewpoint, the strong SEP events observed by the GOES spacecraft are associated both with fast and broad CMEs, likely to drive shocks, and with flares (1; 2), where energy is supposed to be converted through magnetic reconnection in the low corona. There are statistical correlations between the peak intensities and SEP peak fluxes with CME speed (3; 2), but also with flare parameters such as the fluence in the nuclear gamma-ray waveband (4) and the soft X-ray peak flux (2). But the associations often have a broad scatter. The reasons may be manifold: some statistics do not distinguish between SEP events accelerated close to the Sun and energetic storm particles accelerated at the interplanetary shock close to the Earth (2), the acceleration efficiency may depend on the seed population (5) and the shock geometry (6), and the particle flux at Earth depends on the magnetic connection.

It is therefore useful to look for the occurrence of ‘pure flare’ or ‘pure CME’ events, where one can assume that only one of the two possible acceleration scenarios applies. It was shown (7) that the few fast

CMEs with no radio signature of flare-related particle acceleration did not produce conspicuous SEP events detected at Earth, even when they were well-connected. The authors concluded that a CME shock alone was not a sufficient condition for an SEP event. Here we address the opposite question: do strong flares without CMEs produce SEP events? A set of confined strong flares was identified by Wang & Zhang (8) by the absence of a CME or an EUV dimming, which is a well-known on-the-disk signature of a CME. Eleven out of a total of 104 GOES X-class flares (peak energy flux $\geq 10^{-4}$ W m⁻²) during the last solar cycle (1996-2004) were not accompanied by CMEs. Four occurred on the western solar hemisphere, where they could have released SEP onto Earth-connected interplanetary field lines.

We show in Sect. II-A that GOES did not detect an SEP event with these flares. In Sect. II-B we analyse their radio emission, give a more detailed illustration of radio and hard X-ray observations of one event in Sect. II-C, and conclude with a discussion in terms of acceleration and propagation of solar energetic particles.

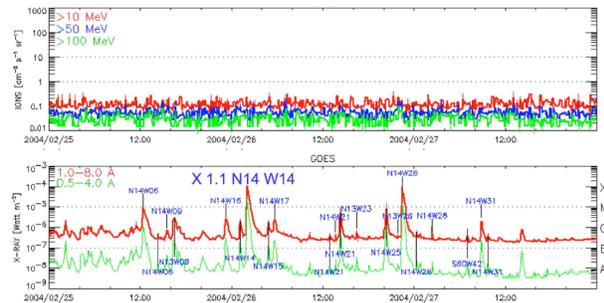


Fig. 1: Time history of the soft X-ray (bottom) and energetic proton flux (top) detected by GOES on 2004 Feb 26 (adapted from the CME catalog, CDAW Data Center, NASA and The Catholic University of America in cooperation with the Naval Research Laboratory).

II. OBSERVATIONS

A. Confined solar flares and SEP

None of the four CME-less flares in the western hemisphere produced an SEP event seen by the GOES satellites. Figure 1, adapted from the SoHO/LASCO CME catalog (http://cdaw.gsfc.nasa.gov/CME_list/), displays the soft X-ray time profile (bottom) and the count rate time profile in the proton channels of the GOES spacecraft between 0 UT on Feb 25 and 24 UT on Feb 27, 2004. The CME-less X class flare (8) occurred N14 W14 at 01:50 UT on Feb 26. There is clearly no

TABLE I: Radio emission from CME-less flares.

Date	microwaves				dm-m- λ	Type II	DH III
	CO(HF)	Peak	CO(LF)	α_{lf}			
2000 Sep 30 23:13	>80 GHz	23:20/35 GHz/5000 sfu	2-1 GHz	4.9	noise storm ?	no	no
2001 Apr 02 10:04	>50 GHz	10:07/15 GHz/1200 sfu		2.6	noise storm	no	no
2003 Jun 09 21:31	>35 GHz	21:37/10 GHz/1000 sfu	610-408 MHz	0.9	II prec > 400 MHz	F/H 360-30 MHz	no
2004 Feb 26 01:50	>35 GHz	01:55/9 GHz/600 sfu	2-1 GHz	5.6	noise storm	no	no

corresponding enhancement of the proton flux measured by GOES in geosynchronous orbit.

B. Radio and hard X-ray emission of the CME-less flares

In order to trace the acceleration and propagation of particles in the corona, we searched for radio signatures of the CME-less flares. Microwave emission (cm wavelengths, $h\nu > 1$ GHz) is produced by gyrosynchrotron emission in magnetic fields $B > 100$ G in the low corona. At longer wavelengths (dm-to-m) the emission comes from higher coronal levels (typically within $1 R_{\odot}$ above the photosphere), generated mostly by subrelativistic electrons. Decametric-to-kilometric type III radio emission reveals electron beams that travel from the corona to the interplanetary medium. We examined the whole Sun radio time histories during the CME-less flares: microwaves (Nobeyama - <http://solar.nro.nao.ac.jp/norp/>, Bern - court. A. Magun, *Radio Solar Telescope Network RSTN* - <http://www.ngdc.noaa.gov/stp/SOLAR/ftpsolarradio.html>), dm-m waves (fixed frequency records RSTN), decametric-to-kilometric waves (WAVES spectrograph aboard the *Wind* spacecraft, (9)).

The results are compiled in Table I. After the start date and time of the soft X-ray burst (8) the columns give parameters of the microwave burst: high-frequency cutoff CO(HF), peak time, frequency (i.e. the frequency where the highest flux density was observed), peak flux density, low-frequency limit CO(LF) and low-frequency power-law spectral index α_{lf} , evaluated in the range (2-5) GHz. The last three columns give a brief characterisation of the emission at dm-m-waves and of the presence of a type II burst and decametric-to-hectometric (DH) type III bursts. These results can be summarised as follows:

- All four CME-less soft X-ray bursts have radiative signatures from relativistic electrons at microwaves.
- None is accompanied by a DH type III burst, suggesting that electrons do not escape to the high corona and the interplanetary space.
- In three of the four events only faint dm-m-wave emission is observed. It exists, however, both before and after the microwave burst, and its time evolution is not correlated with the microwave burst. This is probably noise storm emission, which is independent of the parent flare. Imaging observations with the Nançay Radioheliograph (10) confirmed this for the 2001 Apr 02 event.
- Only one event (2003 Jun 09) has a conspicuous signature at dm-m-wavelengths: at the time

of the microwave emission faint short bursts were seen by the Culgoora Radio spectrograph (<http://www.ips.gov.au/Solar/2/6/1>) at frequencies above 400 MHz. The neat low-frequency cutoff provides evidence that this event also has particles accelerated in a confined magnetic configuration, and no DH type III burst is observed with the microwave emission. But a bright metric type II burst, tracer of a coronal shock wave, is seen a few minutes later. The fundamental band extends from 180 MHz to 30 MHz. There may be a faint DH type III burst in the WAVES spectrum at the time of the type II burst, but no SEPs are observed with this event. The type II burst starts during the decay of the most intense impulsive microwave emission. The faint short bursts above 400 MHz are in the backward extrapolation of the type II burst and could be a precursor as defined in (11).

The absence of DH type III bursts in the four flares confirms their classification as confined events that are well embedded within the parent active regions. This was based in (8) on the localisation of the EUV brightening close to the centre of magnetic flux in the parent active region, and on the strong overlying magnetic flux. The absence of type III bursts at metre wavelengths has long been known to be characteristic of flares near the centre of active regions (12). The microwave spectrum itself provides independent evidence: three of the four events have a low-frequency spectral index $\alpha_{lf} > 2.5$, while the average spectral indices are in general smaller than 2 (13). A natural explanation of steep low-frequency gyrosynchrotron spectra is suppression by the ambient medium (Razin suppression, see, e.g., ch. 4 of 14).

C. A case study: 2004 February 26

The centimetric-to-decametric radio emissions of one of the CME-less flares are displayed in Fig. 2, together with the soft X-ray time profile in the (0.1-0.8) nm wavelength range (top). There is a well-defined impulsive microwave burst, represented by the time profile at 8.8 GHz (labelled RSTN 8800), while metre waves at 245 MHz (RSTN 245) show continued fluctuations that are not related to the flare, but to an independent noise storm. The microwave spectrum is extremely steep at low frequencies (2-5 GHz; Table I). Using the ultrarelativistic approximation, Razin effect becomes noticeable at frequencies below $\nu_R = 19n_e/B$ Hz, where n_e is the thermal electron density, and B the magnetic field strength in cgs units (14). This implies a density above

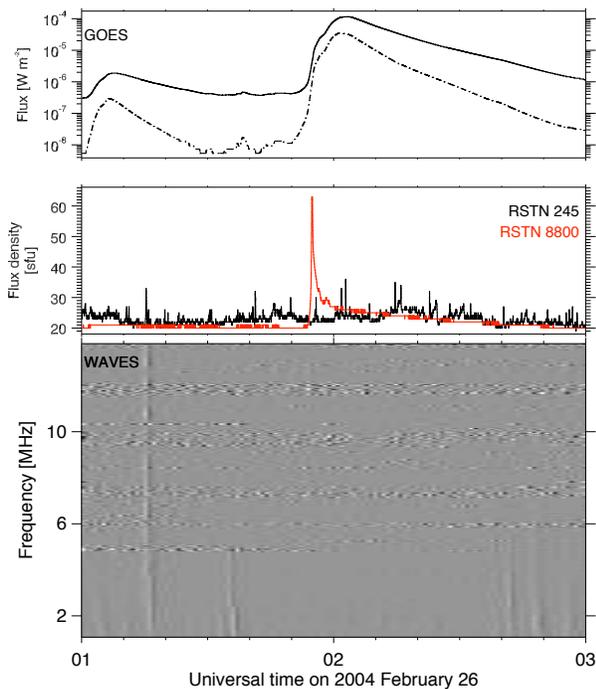


Fig. 2: Time profiles of the whole Sun soft X-ray (top) and radio emission (centre), and of the decametric-hectometric differential spectrum during the CME-less flare of 2004 Feb 26. The 8800 MHz flux density was scaled by 0.08.

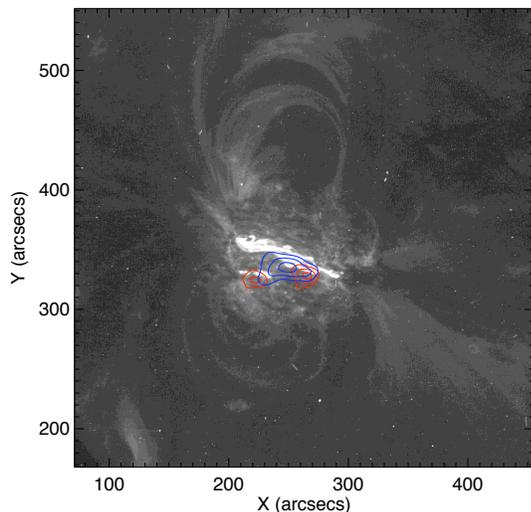


Fig. 3: RHESSI images of X-ray sources at 01:54:42 UT on 2004 Feb 26 (red: 50-100 keV, blue: 6-12 keV) superposed on the nearest TRACE image at 17.1 nm (01:55:01 UT).

10^{10} cm^{-3} if $B > 100 \text{ G}$, i.e. a very dense loop, which is therefore likely to be compact.

The bottom panel of Fig. 2 shows the dynamic differential spectrum at decametre wavelengths, coming from heliocentric distances of roughly $2 R_{\odot}$ (14 MHz) to $10 R_{\odot}$ (1 MHz). The nearly vertical stripes are type III

bursts, emitted near the local plasma frequency or its harmonic by electron beams that travel from the low corona to interplanetary space. Such bursts accompany some episodes of the metre wave noise storm emission (e.g. 01:17 UT), but are clearly absent during the CME-less flare at 01:50 UT.

This is the only of the four flares observed by the *Ramaty High Energy Spectroscopic Imager* spacecraft, RHESSI (15). The time profile in the photon energy range (50-100) keV is similar to that at 8.8 GHz in Fig. 2. In Fig. 3 the hard (red contours) and soft X-ray sources (blue contours) at the event peak are superposed on the image at 17.1 nm taken by the *Transition Region and Coronal Explorer*, TRACE (16). The X-ray emission displays the typical loop-like configuration of impulsive bursts, where hard X-ray footpoints project onto the EUV flare ribbons and are connected by the X-ray source at lower energies. This configuration is embedded within the closed magnetic flux of the active region, as shown by the surrounding TRACE loops.

III. DISCUSSION AND CONCLUSION

A. Particle acceleration in closed magnetic configurations

GOES X-class flares without CMEs produce no major SEP event, as recorded routinely in the ion channels of the GOES spacecraft. The broadband radio observations suggest that whereas electrons are accelerated in the corona during these events, they remain confined in closed structures in the low corona. The evidence is multiple and complementary: absence of DH type III bursts (4/4 events), absence of flare-related metre wave emission (3/4 events), and steep low-frequency spectrum of the microwave burst (3/4 events). In one event we have been able to support the conclusion by hard X-ray imaging. As X-class flares of any importance have been found to produce nuclear gamma-ray lines (17), and since the peak flux at microwaves tends to be correlated with the fluence in nuclear gamma lines (4), we conjecture that protons were also accelerated in the corona during these events, but did not escape either.

From the observational viewpoint the combination of the present study with the earlier finding (7) that pure fast CMEs do not produce conspicuous SEPs means that flares and CMEs are both necessary conditions for an SEP event to occur. This does not necessarily imply that the CME opens the overlying flux and releases the energetic particles. It is both plausible and confirmed by observations (12) that electrons get access to open magnetic flux tubes provided they are accelerated in the outer parts of active regions. Similar conditions are required for flares and CMEs to go together (8). Our result is in line with the finding that proton events at energies above 20 MeV are not only preceded by CMEs, but also by type III bursts from metric to kilometric wavelengths (1), and that these type III bursts come from pre-existing open flux tubes.

B. SEP and type II shocks

It is intriguing that despite the confined character of the energy release in these four events one is accompanied by a coronal shock as revealed by metric type II emission. The mere existence of such a type II burst with an apparently CME-less flare is astonishing, because it is not clear how a pure pressure pulse could generate it in the presumably low- β plasma of the low corona (see recent discussions in 18; 19). The absence of SEPs in this event can hardly be attributed to the confinement of the shock-accelerated particles, because the fundamental type II emission is seen from 180 to 30 MHz, i.e. over a factor 6 in frequency, corresponding to a factor 36 in ambient electron density. In a hydrostatic coronal density model with temperature 1.5 MK this corresponds to a distance of about 0.9 R_{\odot} , which seems far too large for a closed coronal structure. In view of this event we believe that the absence of SEPs with a given solar event cannot be uniquely related to the absence of a shock, as suggested in (20).

C. Conclusion

The major conclusion that we draw from the present study is that the localisation of the acceleration site and the propagation conditions of accelerated particles must be known in some detail to assess the SEP-productivity of a given solar event. Both a flare and a CME seem to be necessary conditions for an SEP event to occur. The difference of local conditions between different events is not taken into account in existing statistical studies. This factor likely contributes to the broad scatter in correlation plots between parameters of the SEPs and the associated solar events. Their ability to trace particle acceleration and propagation over an extended height range makes radio diagnostics a powerful tool for disentangling the complex origin of SEP events.

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