Type II Radio Emission and Solar Energetic Particle Events

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Abstract. Type II radio bursts, solar energetic particle (SEP) events, and interplanetary (IP) shocks all have a common cause, viz., fast and wide (speed ≥ 900 km/s and width ≥ 60°)) coronal mass ejections (CMEs). Deviations from this general picture are observed as (i) lack of type II bursts during many fast and wide CMEs and IP shocks, (ii) slow CMEs associated with type II bursts and SEP events, and (iii) lack of SEP events during many type II bursts. I examine the reasons for these deviations. I also show that ground level enhancement (GLE) events are consistent with shock acceleration because a type II burst is present in every event well before the release of GLE particles and SEPs at the Sun.

Keywords: Coronal Mass Ejections, Flares, Type II radio bursts, Type III radio bursts, Shocks, Solar energetic particles.
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INTRODUCTION

Type II radio bursts are the earliest indicators of shocks from a solar eruption, and hence provide information on solar energetic particle (SEP) events, fast and wide (FW) CMEs, and shocks detected in situ. Type II bursts occur at one or more of the following wave bands: metric (m), decameter-hectometric (DH), and kilometric (km) wavelengths. Metric wavelengths correspond to regions close to the Sun (within 2 solar radii, Rs), while km wavelengths correspond to regions close to Earth. Type II bursts occurring at all wavelengths (m to km) are associated with the most energetic CMEs [1]. Although the connection between SEP events and type II bursts has been known for a long time (see e.g., [2,3]), complete details emerged when observations of DH type II bursts became possible after the launch of Wind. All large SEP events were found to be associated with DH type II bursts [4] and the association rate increased when the type II bursts occur at metric and longer wavelengths [5]. Nevertheless, there are many FW CMEs that do not produce DH type II bursts or SEPs, while some slower CMEs do. This paper attempts to provide an explanation for such occurrences and show that even the SEP events with ground level enhancement (GLE) are consistent with particle acceleration by CME-driven shocks.

OVERALL ASSOCIATIONS

Figure 1 compares the occurrence rates of the following energetic events from the Sun (binned over Carrington Rotation periods) plotted as a function of time: major flares (M- and X-class as observed by the GOES satellite in soft X-rays), fast and wide (FW) CMEs (speed ≥ 900 km/s and width ≥ 60^o) observed by the Solar and Heliospheric Observatory (SOHO) mission's Large Angle and Spectrometric coronagraph (LASCO), major SEP events (proton intensity, Ip, in the GOES >10 MeV energy channel exceeding 10 pfu; pfu is the particle flux unit defined as the number of particles/(cm^2.s.sr), DH type II bursts from the Radio and Plasma Wave (WAVES) Experiment on board the Wind spacecraft, and CME-driven shocks detected in situ by the SOHO proton monitor. The numbers are close to one another and vary with the solar cycle in a similar manner. The only exception is the number of major flares, which has to be divided by 5 to fit the scale. The rates peak in the solar maximum phase (1999-2002), but there are occasional spikes, which are due to some super active regions producing large numbers of eruptions in quick succession. There are many major flares, which are not associated with CMEs or type II bursts and hence the higher rate for M- and X-class flares. All the other events are physically related: FW CMEs drive shocks, which accelerate electrons (producing type II radio bursts) and ions (observed in situ as SEP events). The shocks are also detected in situ when they survive the Sun-Earth transit, which can last anywhere from <1 day to >3 days.

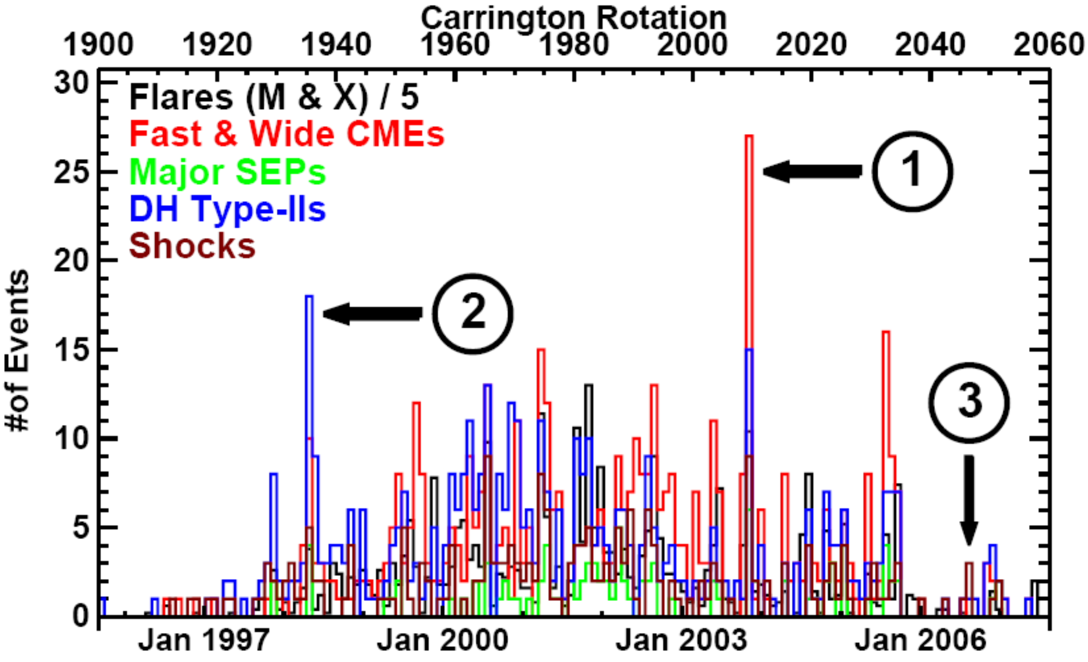

FIGURE 1. Solar-cycle variation of energetic events from the Sun. The number of major flares (M and X class) is divided by a factor of 5 to fit the scale. All the other numbers are of the same order. Examples of FW CMEs without type II bursts and SEPs (1), DH type II without FW CMEs (2), and interplanetary shocks without DH type II bursts and SEPs (3) are marked (see text).

Figure 1 reveals some exceptions to the above picture: (1) FW CMEs without type II bursts (e.g., the two largest spikes in years 2003 and 2005), (2) DH type II bursts without FW CMEs, and (3) in-situ shocks not accompanied by other types of energetic events. We shall explain these deviations in the following subsections.

Fast and Wide CMEs without Type II Bursts

Type II bursts are relatively rare, especially at longer wavelengths, because only the most energetic of CMEs drive shocks far into the IP medium. In all, there were only 344 DH type II bursts over a 10-year period of cycle 23, which means only ~3% of all CMEs produce DH type II bursts [1]. Figure 2 illustrates this using the DH type II burst rate (fraction of CMEs in various speed (V) and width (W) bins associated with type II bursts). The type II association rate drops rapidly for CME speeds less than 1000 km/s and becomes insignificant for CME widths <90°, consistent with our definition of fast (V≥900 km/s) and wide (W≥60°) CMEs. Almost all ≥2000 km/s CMEs produce type II bursts, while there are many CMEs with speeds <2000 km/s not associated with type II bursts. Many of these are fast but narrow (W<60°). Similarly, many of the wide CMEs are not associated with type II bursts, because they are slow. FW CMEs not associated with type II bursts are mostly backsided [6]. It is possible that the radio emission from some of these backside events have difficulty reaching the observer along the Sun-Earth line. However, there are certainly some frontsided, western FW CMEs that are not associated with type II bursts [7]. These CMEs must be ejected into a medium with high Alfven speeds (exceeding 1500 km/s) such that the CMEs drive either weak shocks (that do not accelerate significant number of electrons) or no shocks at all. High Alfven speed can occur when the CME propagates into a tenuous corona and interplanetary medium.

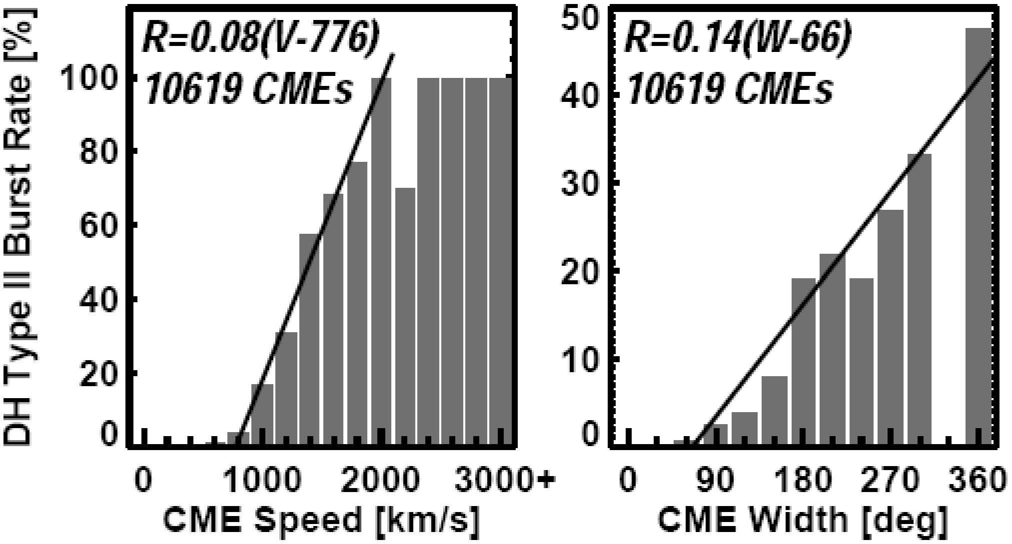

FIGURE 2. The association rate (R) of type II bursts in the decameter-hectometric wavelengths as a function of CME speed (V, left) and width (W, right). All the 10,000+ CMEs observed by SOHO/LASCO have been considered. The 2200 km/s bin contains 10 CMEs, 3 of them being radio-quiet. The linear fits to the rising part of R as a function of V and W are shown on the plots.

About 40% of CME-driven shocks detected in situ (marked 3 in Fig. 1) are not associated with type II radio bursts [8]. Such shocks are due to CMEs that are ~3 times slower than those associated with type II radio bursts and have positive acceleration within the LASCO field of view, suggesting that the shocks form at large distances from the Sun. These shocks are generally weak and probably subcritical (Alfvenic Mach number <1.5). Subcritical shocks may not accelerate significant number of energetic particles [9]. The number of electrons accelerated may not be enough to produce an observable type II radio burst.

Fraction of DH type II bursts Associated with SEPs

Although DH type II bursts are the best indicators of SEP events, not all DH type II bursts are associated with SEP events (marked 2 in Fig. 1). In order to understand this, we have plotted the solar sources of CMEs associated with DH type II bursts in Fig. 3, distinguishing the ones with SEPs (circles) and without (crosses). We have considered SEP events with intensity ≥1 pfu. We see that sources with SEPs are predominantly located in the western hemisphere. The longitude (L) distribution of solar sources peaks at L= 69^o (i.e., W69). Note also that nearly a quarter of the sources (23%) lie beyond the west limb. This is because of a combination of spiral field lines, wide CMEs, and extended shocks that help connect the particles to the observer. Overall, about half of the DH type II bursts is associated with SEP events. The connectivity of the source to the observer seems to be the primary factor that determines whether a DH type II burst is associated with an SEP event. Other factors include CME properties such as speed and width, and the physical conditions in the ambient medium such as the Alfven speed. For example, the five SEP events at longitudes >E30 have an average speed of 1780 km/s, well above the average speed of SEP-producing CMEs (~1600 km/s). Most of the slow CMEs have extremely brief DH type II bursts, which means the shocks did not survive until the coronal heights where SEPs are released. Nevertheless, a few DH type II bursts with speeds <900 km/s did have SEP events, as discussed in the next section.

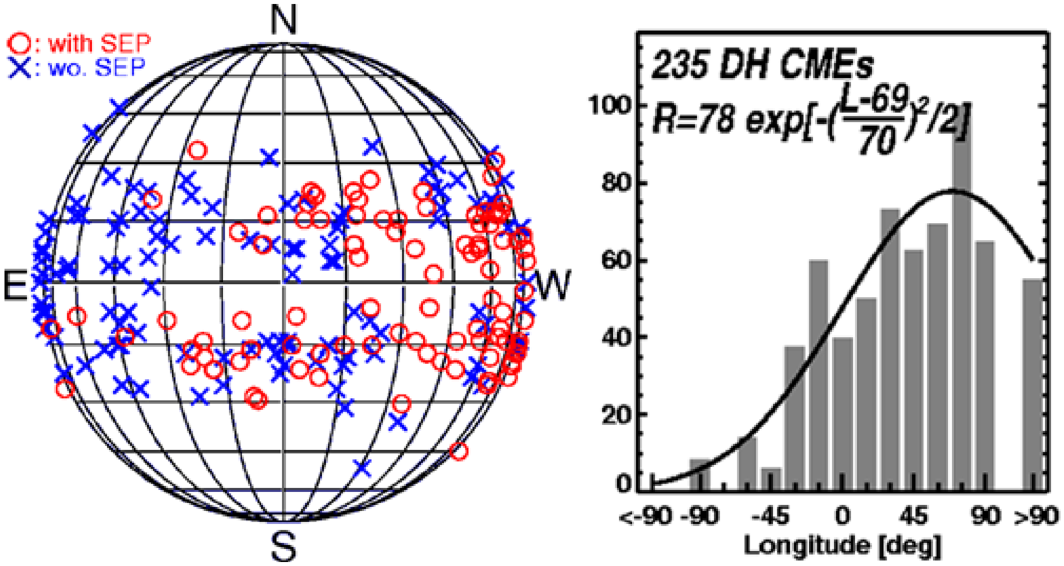

FIGURE 3. (left) Solar sources of DH type II bursts with SEPs (circles) and without (crosses). (right) SEP association rate (R) of CMEs producing DH type II bursts as a function source longitudes (L). The rate peaks at W69 as indicated by the curve fit to the distribution.

Slow CMEs with DH type II Bursts and SEPs

As seen in Fig. 2, about 5% of CMEs in the 700-900 km/s bin are associated with DH type II bursts. Considering only limb events (to avoid projection effects), we found 10 CMEs in this bin, all but one from the western hemisphere. One was a major SEP event (2000 Oct 25), two minor (1 pfu ≤Ip <10 pfu on 2000 June 23 and July 2), one very small (Ip <1 pfu on 2000 June 17), and two had high SEP background (2003 Nov 1 and 3). Thus, only two limb CMEs in the 700-900 km/s bin with DH type II bursts had no SEP association. The four DH type II events with SEP events had a frequency extent of ~10 MHz and an average duration of ~250 min. None of the 8 DH type II bursts with CME speeds in the range 278 – 644 km/s was associated with an SEP event; these type II bursts were extremely brief (frequency extent ~4 MHz confined to > 2 MHz and typically lasting for ~15 min). The two DH type II bursts with the lowest CME speeds (278 and 358 km/s) indicate a real cutoff in CME speed. When we consider the disk events, there are many DH type II bursts with low CME speeds, but the true speeds of these CMEs could be higher due to projection effects. For example, a 478 km/s CME originating from S21W49 was associated with a DH type II burst (see Fig. 4) and a large SEP event (Ip ~10 pfu) lasting for ~2 days. For an Alfven Mach number ~1.5, the Alfven speed in the upstream medium may not exceed 319 km/s (or ~510 km/s when projection effects are taken into account). Note that this is about 3-5 times smaller than the Alfven speed ahead of some radio-quiet CMEs discussed in the previous subsection. Low Alfven speed can occur when the CME propagates into a dense medium, as in this example (see Fig. 4). Only 3 other large SEP events (Ip ≥ 10 pfu) had CME sky-plane speed <900 km/s (832 km/s on 1997 Nov 4, 890 km/s on 2000 Feb 18, and 890 km/s on 2000 Oct 25). The true speeds of these SEP-associated CMEs may be much higher when projection effects are taken into account.

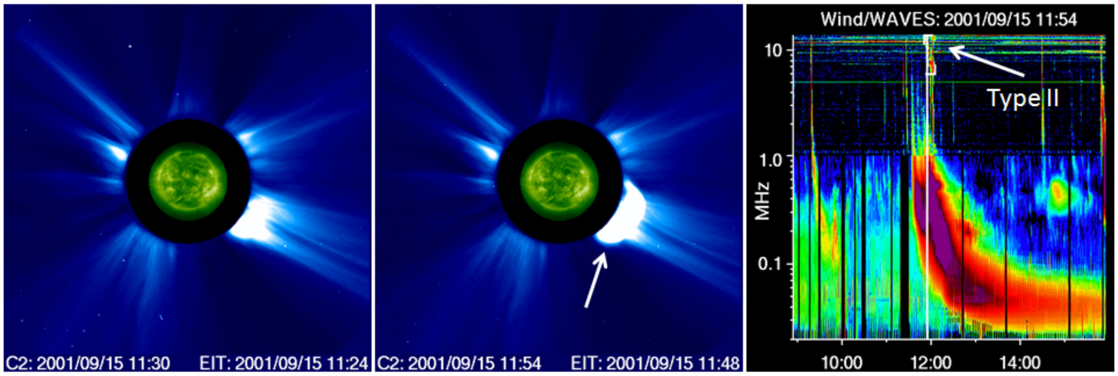

FIGURE 4. A slow CME (middle, pointed by arrow) from a streamer region at the southwest limb (left) and associated with a DH type II burst (right).

TYPE II BURSTS AND GROUND LEVEL ENHANCEMENTS

All the energetic CMEs that produce SEPs are also accompanied by major flares (mostly X-class and some M-class). Therefore, both the flare and shock components should be present in all SEP events, but the detection of the flare component may depend on the connectivity to the observer. This should be true for the SEP events with ground level enhancement (GLE) also. CMEs associated with GLEs have in fact the highest average speed consistent with the fact that GLEs are SEP events with the highest energy [10]. Gamma-ray sources located close to the neutral line [11] suggest that the energetic protons (SEPs) from the flare site seem to be injected over a narrow range of angles. The corresponding upward SEPs from the flare site may also propagate along a narrow cone, so only those SEPs from well-connected flares can be detected by an observer along the Sun-Earth line. The 2001 April 18 GLE event had a flare originating ~30° behind the west limb (see Fig. 5 (left)), yet the GLE event was well observed and ranked fifth largest in cycle 23. It is highly unlikely that the flare component was observed in this GLE event. In fact, only a single GLE event (2005 January 20) may have a discernible flare component [12]; this event was well-connected and happened to be the largest GLE event of cycle 23. Fig. 5 also shows the average CME heights (from the Sun center) at the onset times of metric type II bursts and the release times of GLEs and SEPs (>13 MeV and >40 MeV from SOHO/ERNE). A type II burst preceded all the GLE events, which means a shock was present well before the release of energetic particles. In fact, the shock has to travel additional 2.5 to 5 Rs before SEPs escaped from the shock front. Note also that the higher energy particles are released earlier from the shock front. Thus all GLE events have a shock component.

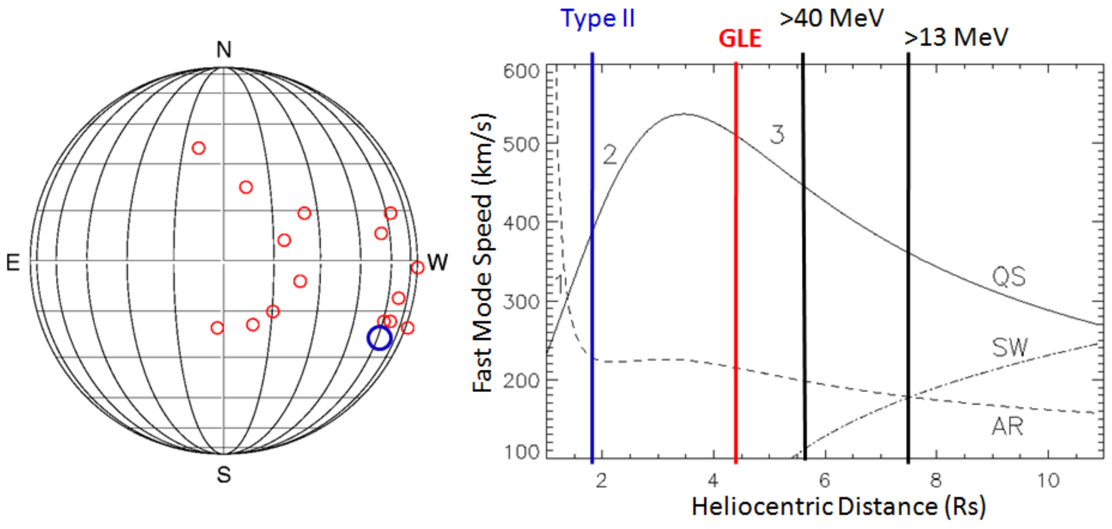

FIGURE 5. (left) Solar sources of CMEs associated with GLE events. The GLE on 2001 April 18 located ~30 degrees behind the limb is denoted by the bigger circle in blue. (right) Fast-mode speed (km/s) in the Quiet Sun (QS) and Active Region (AR), and the slow solar wind speed as a function of the heliocentric distance in solar radii (Rs) from [13]. The vertical lines show the average heights at which metric type II bursts form and energetic particles (GLEs and SEPs) are released.

CONCLUSIONS

This paper summarizes various aspects of the association between type II radio bursts and SEP events. The main conclusions are: (1) Type II radio bursts at frequencies below ~ 14 MHz originating from the western hemisphere of the Sun are excellent indicators of large SEP events. The distribution of SEP sources is centered on W69 with very few sources beyond E45 and a sizable number beyond W90. (2) Fast and wide CMEs not producing type II bursts (or SEPs) can be explained by high Alfven speed in the ambient medium so that they drive either weak shocks or no shock at all. Similarly interplanetary shocks without radio emission seem to be weak (subcritical) that they do not accelerate significant number of particles. (3) Some slower CMEs produce Type II bursts and SEPs when they are launched into an ambient medium of low Alfven speed. Thus, a 400 km/s CME can be a "fast" CME, while a 1500 km/s can be a "slow" CME depending on the ambient Alfven speed. (4) One of the best evidences that CME-driven shocks produce GLE events is the event from an occulted eruption on 2001 April 18, which occurred about ~30^{o} behind the west limb. Given the spatial localization of the protons producing gamma rays, any flare component of the GLE particles should have been occulted. (5) Another evidence for the shock acceleration is the delayed release of GLE particles from the type II onset. Thus a shock is present nearer to the Sun well before the release of GLE particles.

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