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Are there two classes of solar energetic particle events?

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Abstract. In the current paradigm, solar energetic particle events are considered to belong to one of two classes. In one class (impulsive), particle acceleration is related to flare processes, most likely resulting from magnetic reconnection. The clearest signature of this flare process is the presence of type III (fast–drift) radio bursts caused by electron beams. In the other class of particle event (gradual), flares are considered to be of no importance and the particles are presumed to be accelerated at shocks driven by coronal mass ejections (CMEs). These particle events are the ones with the highest ion intensities. In a recent study it has been found that *all* major proton events are preceded by a fast–drift radio burst indicating that flare processes occur in gradual events as well. However the radio bursts usually start relatively high in the corona. It is also found that the largest of the particle events in the first class are associated with CMEs suggesting that the 'two class' paradigm needs revising. It is proposed that the flare process occurs in all particle events and that the characteristics of the accelerated particles are determined by the height of the acceleration region in the corona. Low coronal heights will produce abundances and charge states typical of hot plasma whereas acceleration at high heights will result in abundances and charge states typical of the solar wind. Hence, one expects events with variations over a range of values. If the event includes a CME and an associated shock which has access to the flare particles for further acceleration, a long–lasting, high intensity particle event will result.

1 Introduction

The current paradigm of two classes of solar particle events has its origins in the earliest solar radio observations which showed that major solar flare events have two 'phases' (Wild et al., 1963). Fast–drift bursts, called type III, occur during the impulsive phase of solar flares and are followed by slow–drift bursts, called type II, that occur during the main or gradual phase of flares. Their relative timing is such that the type III bursts precede the type II bursts. The drift rate and the starting frequency of the type II burst are consistent with a common origin for the type II and type III bursts. Thus it may be deduced that type II bursts are closely linked to type III bursts and to flares. Type II bursts are assumed to be caused by shocks because their drift rates indicate speeds of about 1000 km/s. Wild et al. (1963) suggested that these shocks accelerate electrons and protons to high energies. However, there was no direct evidence to support the suggestion. About 20% of major proton events have no associated type II burst. Type III bursts are caused by electron streams with energies of a few tens of keV. Wild et al. (1963) assumed that no protons were accelerated in the type III/flare process. We now know that this is incorrect and that the flare process can accelerate electrons to tens of MeV and protons to GeV energies (Miller et al., 1997). A direct link between flares and proton events was challenged when it was found that some weak flares could be associated with major proton events. It was suggested that protons are accelerated at shocks in front of coronal mass ejections (Cliver et al., 1983) with the assumption being that the type II burst originated in this shock. It is now claimed that flares are irrelevant in major proton events (Reames, 1999) and yet type II bursts, as stated above, are a flare phenomenon, Furthermore there is reason to question the idea that shocks driven by coronal mass ejections (CMEs) are the principle accelerators in major proton events because CME speed does not organise particle intensities particularly well. Kahler et al. (1999) report a spread in particle intensity over 4 orders of magnitude for a speed range of only 200 km/sec. Also there have been a few relatively fast CMEs originating on the western hemisphere of the Sun with no associated particle increase. On the other hand, the observations can be understood if major flares result from CMEs and the CME–driven shock re-accelerates particles initially energized by flare processes. Recent work (Cane, 2001) provides evidence that all solar particle events are preceded by flare processes.

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2 Data Analysis

An intercomparison has been made of proton events, (as measured by the Goddard experiment on IMP 8), CMEs (as observed by LASCO) and, radio bursts (as observed by the WAVES experiment on Wind and from the ground). (For details see Cane, 2001.) All the proton increases having a 24-29 MeV intensity above 10^{-3} particles/ (cm^2-sec-ster-MeV) occurring when LASCO was operating were associated with a CME, and all were preceded by a fast–drift radio burst. The majority of the associated CMEs were large (i.e. with a projected angular extent $\geq 140°$). Some of the particle events would be described as 'impulsive' in that they had high e/p and Fe/O ratios, and durations of a day or less, and yet they were preceded by a CME. The remaining particle events would be described as 'gradual', and yet were preceded by fast–drift (flare–related) radio bursts. Clearly the presence of a CME is *not* what determines abundance variations and flares *are* important.

One of the reasons why shock acceleration is attractive is it allows for particle acceleration promptly over a wide range of heliolongitudes. Although in the later stages of major particle events it is clear that shock acceleration is important, because connection to an approaching shock organises particle intensity profiles as a function of the source location (Cane et al., 1988), it is not clear that shocks are the only way in which magnetic access to remote regions is achieved. For example, Richardson et al. (1991) showed how direct access to an eastern hemisphere region can occur when Earth is inside a CME with its associated looped field lines. Recent observations from Yohkoh, SOHO and TRACE have shown that huge loops connect separate active regions and that multiple active regions are affected when major CMEs occur. Fast–drift bursts can be used to trace field lines from the Sun into the interplanetary medium. The radio emission is plasma emission and the frequency emitted is inversely related to the ambient density. Thus, since the solar wind density decreases with distance from the Sun, a propagating electron beam causes a burst drifting to lower frequencies. Radio emission cannot propagate below the local plasma frequency so emission is generated at an observer's local plasma frequency only if the electron beam actually is intercepted by the observer. This means that the low frequency extent of a fast–drift burst can be used to determine whether there is field line connection to the source region of a particular radio burst. If a fast–drift burst extends to the local plasma frequency then electrons must have travelled directly along field lines from the flare region to the observer. The low frequency extents of the fast–drift bursts associated with all the large CMEs that occurred in 1998-2000 were examined and compared with the local plasma frequencies. (Most large CMEs with speeds >600 km/s are associated with fast–drift bursts.) The peak proton intensities associated with such CMEs had previously been determined. Figure 1 plots the associated proton intensities as a function of the flare heliolongitude. The filled circles represent events in which the fast–drift bursts indicate good magnetic connection, open circles no connection and asterisks poor connection. It is clear that the low frequency extent of bursts organises the particle intensities. For those western hemisphere CMEs without associated particles (some of which have speeds above 700 km/s) there was no magnetic connection to the flare region. For the eastern hemisphere CMEs with particles there is magnetic connection. Thus it is not necessary to invoke shock acceleration to explain prompt particles from regions that are not at mid–western longitudes. Fast–drift bursts allow the magnetic connection to be directly illustrated. Note that the ~20 keV electrons arrive at about the time that the local radio emission commences. Tracing the radio emission back indicates when the electrons left the Sun. This time is often earlier than the 'solar release time' (e.g. Krucker et al., 1999) based on assumptions about electron speeds and path lengths and indicates that these assumptions are incorrect.

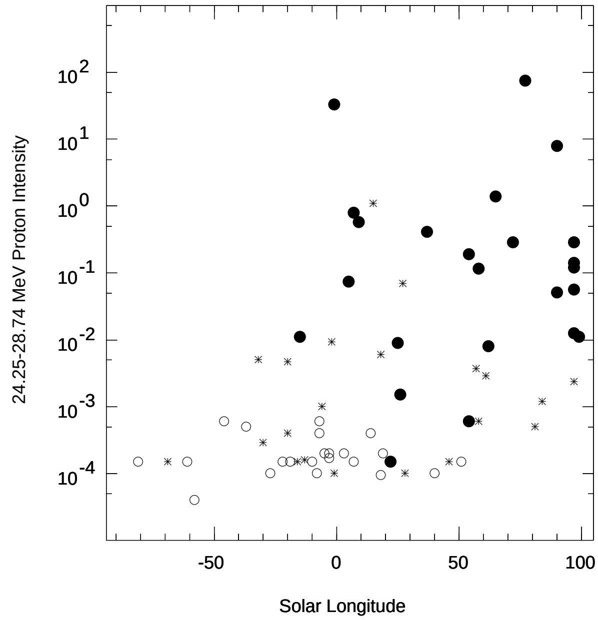

Fig. 1. Proton intensities as a function of flare heliolongitude for large CMEs. The symbols indicate whether the associated fast–drift bursts, and hence the associated particle beams, clearly intercepted the Earth (filled circles), probably intercepted the Earth (asterisks) or missed the Earth (open circles).

It is well known that type III bursts are quite common and generally are not accompanied by measurable intensities of protons, so one would expect that the fast–drift bursts associated with major proton events should have some attribute which distinguishes them from normal type III bursts. The distinguishing feature is that the fast–drift bursts associated with major proton events start at relatively low frequencies (i.e. high coronal heights) during the gradual phase of flares. Above 10 MHz they are usually associated with type II bursts and indeed appear to grow out of type II bursts. They last for about 30 minutes at 10 MHz, in comparison to the type III bursts in the impulsive phase, which are often also present, which last about 5 minutes. They are very intense below 10 MHz as may be seen in Figure 2. Originally it was thought

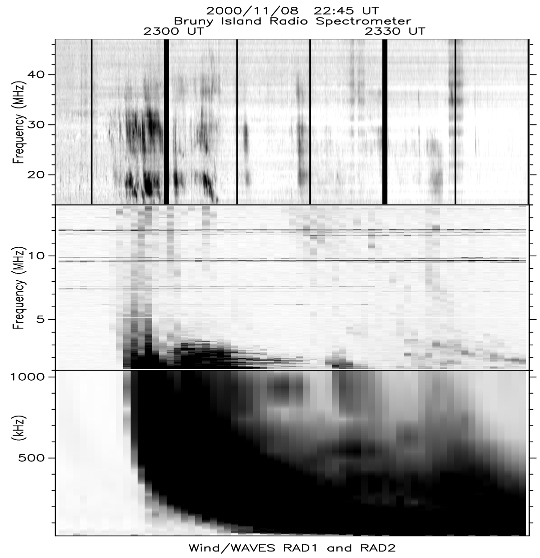

Fig. 2. An example of a huge fast–drift burst associated with a major proton event. Note that for this event there is no type II burst above 5 MHz; the faint, slow–drifting feature near 1 MHz, near the right hand edge of the middle of the plot, is probably radio emission from a shock driven by the associated CME.

that the electrons causing these gradual phase type III bursts were shock accelerated (Cane et al., 1981) but it now seems unlikely that this is the case (see Reiner et al., 2000; Cane, 2001). Furthermore it seems likely that much of the emission attributed to coronal shocks is in fact generated by electron streams accelerated in flare processes. This then explains the confusing reports for many events in which one observatory reports type III bursts and another reports type II, and why for some major events no type II is reported but just a long lasting group of type III bursts. The difference between these type IIIs and a group of normal type IIIs is that the starting frequencies of the type III and/or II bursts progress rapidly to lower and lower frequencies. One obvious way in which this could occur is if the electron source moves to greater coronal heights as a function of time. Such a source is a region of reconnection associated with a CME.

Consider now intensity profiles and abundance variations. The upper panel of Figure 3 illustrates particle (electron and proton) data for two major proton events. The lower panels of Figure 3 illustrate particle intensities for two small proton events. All events were associated with CMEs and the sky-plane speeds are indicated. The upper events originated near central meridian and so the CME speeds are below the true speeds, because of projection, but probably to the same extent. The speeds differ by more than a factor of 2 and yet the two events have very similar particle intensities. The CME of June 2000 had the highest speed of the four events but there is only a small proton increase. The proton intensities of the events in Figure 3 are not organised by the presence or absence of a CME nor by CME speed. Consider now the radio bursts. The upper events were preceded by type II bursts in the 90-10 MHz range and the Jan. 1998 event by type II activity in the 95–17 MHz range. None of the events were preceded by type III bursts at frequencies above 20 MHz. In contrast, the June 2000 radio event, which has the highest electron to proton ratio, consisted of type III bursts starting at 180 MHz. (One observatory reported 3 minutes of type II activity). The events were chosen to show that there is a continuum of particle characteristics. It is not possible to place the lower two events in the two classes of the current paradigm. What separates out the event with the high electron to proton ratio is the presence of a normal type III burst.

The first large events in solar cycle 23 had enhanced abundances of heavy ions and caused some confusion. But they were preceded by type III bursts starting at high frequencies. For example, the May 6 1998 event was preceded by type III activity above 200 MHz and type II activity starting around 150 MHz. Previously it was found that particle events with high e/p ratios were associated with strong type III bursts (Cane et al., 1986). It seems probable that abundance variations result because of the varying coronal heights at which particles can be accelerated.

Finally it might be questioned whether the fast–drift radio bursts are entirely relevant since they are produced by streams of low energy electrons and one is more interested in high energy ions. A comparison of the intensity profiles of the electrons that produce the radio emission with the profiles of high energy protons with similar speeds (i.e. $>$100 MeV) reveals that these particles arrive at the same time and have very similar profiles (see Cane, 2001).

3 Summary and Discussion

It has been found that major particle events seen near Earth are *always* accompanied by fast–drift radio bursts that extend to the local plasma frequency and with CMEs. The association of CMEs with a certain type of fast–drift burst suggests that the acceleration of the causative electron beams occurs in reconnecting regions associated with the departure of the CME. These bursts have been found to be a necessary and sufficient condition for a major proton event. The low frequency extents of the bursts shows whether flare particles reach the Earth and can be used to organise proton intensities. The closeness in morphology of the causative $\sim$20 keV electron intensity-time profiles with those of $>$100 MeV protons suggests that the two species are accelerated at the same time by the same ‘flare’ process. This indicates an important flare contribution for major proton events. Although the ‘flare process’ is not well understood it is clear from gamma ray observations that such a process exists and can accelerate electrons to tens of MeV and protons to GeV energies. Based on a comparison of the starting frequencies of radio bursts and the abundance characteristics of energetic particles it seems likely that the height of the flare process determines the relative abundances of the accelerated particles. Although many events fall at either end of the abundance range it is clear that there is likely to be a continuum of events and it would be

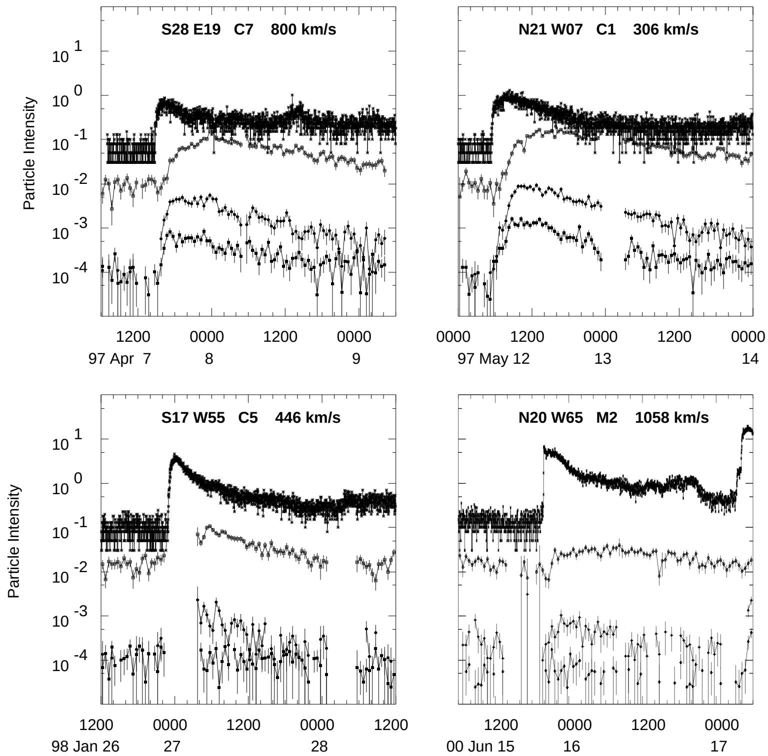

Fig. 3. Four particle events, all associated with flares, radio bursts and CMEs. The top curves are electron intensities for the energy range 127-225 keV from Wind. The three lower curves in each panel are proton intensities in the energy ranges 6–11, 24–29 and 43–63 MeV from the GSFC experiment on IMP8. The proton intensities are particles/(cm^2-sec-ster-MeV) whereas the electron intensities are 10*particles/(cm^2-sec-ster-keV). Flare location and peak intensity in soft Xrays are noted along with the speed of the associated CME.

better to devise a new system for describing particle acceleration processes. Furthermore it is important that modelling of shock acceleration should consider the flare accelerated particles that exist in the vast majority of events and in particular those that extend above about 10 MeV, which is the maximum energy that results when only solar wind particles are accelerated by a CME–driven shock.

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