CME-driven Coronal Shock Acceleration Of Energetic Electrons

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Abstract. 53 impulsive (38-315 keV) near-relativistic solar electron events with beam-like pitch-angle distributions were observed by the ACE/EPAM experiment while the SOHO/LASCO coronographs were observing coronal mass ejections (CME) between 2.5 and 30 Rs. Simnett, Roelof and Haggerty [in companion papers to be published in Ap. J., 2002] report a close association among the impulsive electron beams, solar electromagnetic emissions, and western hemisphere CMEs, jets, etc. They find that the electron injections are delayed ~10 minutes after the electromagnetic emissions and ~20 minutes after the CME launches, so that the electron release occurs when the CME has travelled 1-2 Rs beyond the CME launch altitude. The median exciter speed of the associated solar type III radio bursts (deduced from WIND/WAVES decametric spectrograms) is 0.08c, implying that the characteristic electron energies in the exciter front are only a few keV. Since no prompt near-relativistic electrons are injected until ~10 minutes after the type III burst, the energy spectrum of the type III associated electrons must be steep at these energies. Therefore the near-relativistic electrons that must be present to produce the microwave and hard X-ray bursts also do not escape promptly with intensities measurable by ACE/EPAM. Inverse correlation between the finite delays of near-relativistic electrons after the CME launch confirms that the electrons are injected when the CMEs are ~1-2 Rs above the photosphere. The positive correlation between CME speed and electron intensity (as well as spectral hardness) is consistent with the process of shock acceleration. Therefore we conclude that the simplest explanation of the observational associations is that the electrons are accelerated by CME-driven shocks in the corona at altitudes ~1-2 Rs above the photosphere. We see no reason why ions should not also be accelerated concurrently in the corona by this same process, although the final velocity of the ions may be less than that of the electrons.

INTRODUCTION

The Sun is a prolific source of energetic electrons, but the processes governing their acceleration and release have remained elusive. Recently it has been recognised (Haggerty and Roelof, 2002) that the best way of identifying within a few minutes when such electrons are released from the Sun is only to analyse events whose pitch angle distribution forms a highly anisotropic outward flowing beam. A spacecraft, say at 1 AU, is connected magnetically to the Sun on one side, and to some region beyond 1 AU on the other side. Electrons released from the Sun become field-aligned within a few solar radii, and thus will first cross the 1 AU radius as a beam. However, somewhere, normally beyond 1 AU, significant scattering takes place, probably at compression regions where fast and slow solar wind streams interact. This means that for electrons released onto distant field lines which do not immediately pass through the observer, back-scattering from the interaction region can produce an onset which is relatively isotropic. Thus an impulsive intensity increase is not in itself indicative of a recent release unless it is highly anisotropic. Beam-like events have for many years been referred to as “scatter-free”. A related criterion for identifying scatter-free propagation of the earliest-arriving electrons is their velocity dispersion (Krucker et al., 1999). The difference between injection and onset times must be equal to the distance travelled divided by the electron velocity.

Haggerty and Roelof (2002) have identified scatter-free electron events in the ~40-300 keV energy region using the EPAM instrument on the ACE spacecraft, which is near the L₁ Lagrangian point on the Earth-Sun line. They showed (their Fig. 1) that is was possible from the onset times in different electron energy bands to derive an injection time at the Sun. When they examined radio, X-ray and optical emission from the Sun, they found that the electron release time was delayed by at least 10 minutes from the peaks of the microwave and hard X-ray emission (when present) and that the events were frequently associated with chromospheric activity in the western hemisphere. The latter is not surprising, as the nominal magnetic connection from ACE back to the Sun is to a longitude around W60°. This will be discussed in more detail in section IV. They also found that the scatter-free electron events were accompanied by de-
The observations were made with the WAVES instrument (Bougeret et al., 1995) on the WIND spacecraft, and had drift rates such that the characteristic energies of the electrons in the exic front were only a few keV (Haggerty et al., 2001). This, plus the delayed injection of the near-relativistic electrons, led Haggerty and Roelof to conclude that the electrons that produced the microwave and hard X-ray emission in the chromosphere do not escape promptly into space at intensities measurable by ACE/EPAM; nor do near-relativistic electrons escape at the time of the high coronal type III bursts.

Simnett et al. (2002) searched for CMEs in association with the beam events, and found that the majority of the latter occurred in association with a west-hemisphere CME. In this paper we review these results and examine what inferences may be made from the data to improve our understanding of electron acceleration and release from the solar environment.

THE OBSERVATIONS

The electron observations we use were made with the EPAM instrument (Gold et al., 1998) on the ACE spacecraft from 25 August 1997 to 9 September, 2000. Solar electrons were measured in either the LEFS60 or the LEMS30 system; for the latter the electrons were magnetically deflected into a separate detector, thus eliminating the possibility of ion contamination which exists in the LEFS60 telescope. However, at the onset ion contamination is not a problem because they arrive much later. The LEFS60 and LEMS30 telescopes are oriented on the spinning ACE spacecraft at 60° and 30° respectively to the spin axis; and the spin axis is generally within a few degrees of the Sun-Earth line. Thus these telescopes are well suited for studying prompt solar electron events.

Fig. 1 shows an example of the beamed electron event on 20 February, 1999. Other examples are given in Simnett et al., (2002). Four of the eight sectors of the LEFS60 telescope are at the background level until after 16:00 UT, which is some 15 minutes after the intensity maximum. Inset is the pitch cosine distribution, normalised to the intensity in the peak sector, from 15:38-15:40 UT. The measured angular width is comparable to the opening angle of the telescope collimator, so the actual beam width is probably unresolved. The strong beam is maintained for over 30 minutes. This event is typical of the electron events we have used in this study.

The CME observations were made with the LASCO (Brueckner et al., 1995) C2 and C3 coronagraphs on the SOHO spacecraft, which is also near the L1 point. Simnett et al. (2002) examined running difference images for 52 out of 79 scatter-free electron events analysed by Haggerty and Roelof (2002), and were able to determine the onset times at a nominal 1R太阳. The other events occurred when LASCO was not observing. We have since found another event, so the statistics in this paper are from 80 events, of which 53 are observed by LASCO.

We also made use of data from the WAVES instrument on the WIND spacecraft; and from Solar Geophysical Data, (US Dept. of Commerce, Boulder, CO).

ASSOCIATIONS AND CORRELATIONS

Haggerty and Roelof (2002) showed that 46 out of the original 79 electron events occurred in association with an Hα flare. However, when they allowed for the fact that the distribution of flares extended beyond the west limb, a conservative estimate of the true fraction of Hα flare associations was ~85%. Thus most of the beam events were associated with chromospheric flare activity and the location of such activity was consistent with good magnetic connectivity to ACE. The majority of the beamed events were observed in 3 or 4 of the EPAM electron channels. Using the onsets at the highest measured energies, Haggerty and Roelof (2002) were able to determine the injection time at the Sun. This time is, of course, only the beginning of an extended injection phase that may last tens of minutes. The injection must last for at least as long as the duration of the beam-like anisotropy. In the example in Fig. 1 the duration is 40 - 60 minutes, typical of most of the beams we have detected.

The majority of the beamed electron events are also
associated with CMEs observed (in projection onto the plane of the sky) by LASCO off the solar west limb. Of the 53 events occurring during LASCO observations, 48 were distinct enough that the height-time profile could be mapped back to the Sun. We define, for consistency, a CME onset to be when the height-time profile maps back to 1 \( R_\odot \). This radius is somewhat artificial as the erupting structure must form above the photosphere; however this serves as a useful reference point from which to construct a statistical analysis. Of the 48 CMEs, 35 we considered as “classical” CMEs (including 6 halo events) which are large, loop-like structures, as distinct from small blobs.

From the two data sets we can construct a histogram of the time between the CME onset and the start of the electron injection, and this is shown in Fig. 2 (from Simnett et al., 2002). It is clear that the distribution is peaked at around 19 minutes, with the electron injection delayed from the CME launch. It is useful to examine in more detail the accuracy or confidence we have in this result, which is based on extrapolations of two entirely independent data-sets.

Krucker et al. (1999) discussed the origin of impulsive electron events below 300 keV and concluded that there were two types. Low energy events, below 25 keV, were released in good temporal association with metric type III radio bursts, although timing of the injection to within a few minutes becomes more difficult at lower energies: a 5 keV electron takes 70 minutes to travel along the interplanetary magnetic field line to Earth. The higher energy events, comparable in energy to those we discuss here, were delayed by up to half an hour from such bursts. Haggerty and Roelof (2002) have also analysed the timing of the beam events (lower energy threshold 38 keV) with respect to type III emission, and reach a conclusion consistent with Krucker et al., for the higher energy electrons. They estimated that the uncertainty in the electron release time is of the order of three minutes. Recall that it is only the low energy electrons that are released at the same time as the type III radio emission is observed; the higher energies (>38 keV) are delayed.

Although many of the CME height-time profiles show a constant speed, there is inevitably a finite error associated with the estimated onset time. This is difficult to establish, and an attempt to do this for each CME is not fruitful, as the notional starting altitude is somewhat arbitrarily chosen at 1 \( R_\odot \) simply for consistency. We estimate that the uncertainty in CME onset time is also a few minutes. However, we have a different way to verify this, namely by examining the shape of the distribution in Fig. 2. If the two times were physically unrelated, then the expectation value of the delay would be zero. Any uncertainties in the estimates of either the CME launch time or the electron injection time would broaden the distribution; systematic errors could shift the median. If we interpret the distribution in Fig. 2 as a Gaussian plus a tail that includes the events with long delay times, the half width gives a value of the standard deviation, \( \sigma \sim 10 \) minutes. In order to assess the statistical significance of the median delay (19 ±10 minutes), suppose that the half-width were entirely due to measurement uncertainties in the estimates of the CME launch time (\( \sigma_{\text{CME}} \)) and the electron injection (\( \sigma_{\text{elec}} \)).

If we suppose that:

\[
\sigma = (\sigma_{\text{CME}}^2 + \sigma_{\text{elec}}^2)^{1/2}
\]

this gives \( \sigma_{\text{CME}} \approx \sigma_{\text{elec}} \approx 0.7 \sigma = 7 \) minutes, assuming that the uncertainties are comparable. However, we seriously doubt that the timing uncertainties could be this large. That is because there is only one event with a negative delay, and we would consider it a remarkable coincidence that a putative systematic error could combine with random measurement errors to give delays that are essentially always positive. Since the actual delay times must have some variation from event to event, any random measurement error must be < 7 minutes. Therefore our earlier estimates of a few minutes for the uncertainty of both the electron injection and CME onset are justified by the data in Fig. 2.

For each event we may determine the height of the CME at the time of the electron injection, and the distribution of these distances is shown in Fig. 3 (from Simnett et al., 2002). The CME was below a projected altitude of 5 \( R_\odot \) for the majority (44) of the injections. The median value of this distribution, ignoring the 4 events beyond 5 \( R_\odot \), is 2.3 \( R_\odot \). There is a further consideration, namely that the CMEs are seen projected onto the plane of the sky. This will underestimate some CME speeds, but not...
Number of CMEs

Distance (Rs)

>5

FIGURE 3. The height of the CME above Sun-center at the time of the electron release in the corona. (After Simnett et al., 2002)

their onset times. However, the effect is relatively small, as it varies as the cosine of the angle out of the plane of the sky and our CMEs were almost all visible off the west limb. In view of this effect we regard 3.0 R$_\odot$ as a more conservative estimate of the mean radius for electron injection.

We have examined the CME speeds corresponding to the events. Fig. 4 (from Simnett et al., 2002) shows the distribution of CME speeds versus the electron release delay time from the CME onset time. There is a trend towards anticorrelation. Note that the 8 events with long delays follow the general trend because they correspond to the slowest CMEs. The continuity of this ordering with respect to CME velocity shows that there is no separable sub-class of near-relativistic electron injections. This anticorrelation is what produces the injections at a relatively small range of coronal altitudes, as indicated by Fig. 3. We would not expect a perfect anticorrelation as the magnetic topology of the high corona is not expected to be homogeneous, nor to have a simple radial dependence.

There are two other features of the electron events which are worthy of note, namely the peak intensity and the energy spectrum. Fig. 5 (from Simnett et al., 2002) shows the peak intensity for the four electron channels in the LEFS60 detector. We have used this as it has a larger geometrical factor than the deflected electron detector, and is therefore statistically more accurate. As mentioned above, ion contamination is negligible as any ions associated with the events which could satisfy the detector logic requirements for electrons take hours to reach Earth, and cannot contribute to the peak intensity in these electron events, which typically have intensity-time profiles like Fig. 1. The lines drawn through the points are least-squares fits to the data. The positive slope to each line increases with energy. This means that the faster (slower) the CME the more (less) efficient it is at accelerating electrons, and moreover that the effect is strongest for the highest energy electrons that we measure.

Fig. 6 (from Simnett et al., 2002) shows the power law index of the spectrum, defined from the intensities measured in adjacent electron energy channels, as a function of CME speed. The straight lines represent least-squares fits to the points. The decreasing slopes mean that the faster (slower) CMEs produce harder (softer) electron spectra. This trend is slightly stronger at higher energies. There might be a sensitivity effect, in that small events with steep spectra will not appear; however, if we accept the trend evident in Fig. 4, these should correspond to lower speed CMEs. Therefore they would have increased the anticorrelation had they been measured.

Physically the trends in Figs. 5 and 6 show that faster CMEs not only accelerate more electrons, but they also produce harder electron spectra. Both trends are consistent with the general theory of shock acceleration; it is likely that most of the CMEs drive shocks in the corona near the Sun. Both trends can be made even more visible by constructing composite spectra derived from the least-squares fits in Fig. 5. These linear fits of the log-mean intensity (at each of the four channel energies) to the associated CME velocity can be converted to four-point spectra of the form $j(E,V)=j_0(E)exp[a(E)V]$, where $j_0(E)$ is taken from the ordinate intercepts in each panel of Fig. 5 and $a(E)$ is the slope of each fit (indicated in the panel). These composite spectra are plotted in Fig. 7 and each is labeled with the associated CME velocity 200<V<1200 km/s. It is clear that (1) the faster the CME, the more intense the 40 - 300 keV electron intensity tends to be, and (2) the faster the CME, the harder (flatter) is the electron spectrum. Trends (1) and (2) are consistent with shock acceleration theory.

DISCUSSION

It was the comprehensive study of electron events observed near solar minimum by Krucker et al. (1999) that called out the common occurrence of significant delays (~10s of minutes) of near-relativistic electron injection after prompt solar flare electromagnetic emission. However, Krucker et al. interpreted their results in terms of two classes of scatter-free electron events, namely those with negligible delays and those with significant delays with respect to metric type III bursts. As pointed out in our discussion of Fig. 4, we find only one inseparable class of events, with delays ranging from the small to
FIGURE 4. The electron injection delay from the CME launch time versus the CME speed. (After Simnett et al., 2002)

FIGURE 5. The electron peak intensity in the four electron channels of LEPS60, as a function of the CME speed. (After Simnett et al., 2002)

the large because the small delays are associated with fast CMEs and the large delays with slow CMEs. We believe the results of Krucker et al. are actually consistent with this latter interpretation to which we were led by the close associations we found with CMEs. This consistency can be seen in Fig. 8 which shows the distribution of the 58 3DP scatter-free electron injection delays (Krucker et al., 1999) with that of our own 48 EPAM events associated with metric type III bursts (taken from the list of Haggerty and Roelof, 2002). Allowing for a possible solar cycle effect (see below), we think that both distributions represent a single class of events.

Solar electron acceleration and emission is clearly complex and Krucker et al., (1999) have suggested that it could be solar cycle dependent. Low energy electron events without metric type III associations such as those reported by Potter et al., (1980) from ISEE-3 during solar maximum had around 40% of total events that were measurable only below 15 keV. Krunker et al. point out that from the WIND data around solar minimum, events seen only at low energies are rare. This suggests that more than one physical process must be responsible for the acceleration. It seems clear that the low energy events

FIGURE 6. The two point electron intensity power-law spectral exponent derived from adjacent pairs of the four deflected electron channels as a function of CME speed. The upper plot is from DE1 and DE2; the middle plot is from DE2 and DE3; and the lower plot is from DE3 and DE4. (After Simnett et al., 2002)
FIGURE 7. “Composite” electron spectra constructed from the least-squares fits of intensity vs. CME velocity from Fig. 5. See text for details. The velocity dependence is consistent with that generally predicted by shock acceleration theory.

FIGURE 8. Distributions of near-relativistic electron delays after solar type III radio bursts: 58 events from WIND/3DP (Krucker et al., 1999) and 48 ACE/EPAM events taken from the list of Haggerty and Roelof (2002).
are formed from a process taking place high in the corona (Lin, 1985), whereas a typical high energy event comes from a CME-driven shock. The events are only seen at a given spacecraft under favorable magnetic connections.

However, the situation is more complicated than suggested by this simple analysis. LASCO observations show that there are many CMEs which are fast enough to drive shocks through the corona. Simnett et al (2002) estimated conservatively that if all such CMEs accelerated near-relativistic electrons, there should be at least five times as many electron beams seen at ACE than we have detected. The clue to the puzzle lies in the near perfect association of strong decametric type III bursts seen by the WIND spacecraft in association with the electron beams. Haggerty et al., (2001) showed that the exciter speed was equivalent to electrons of only a few keV. Therefore we believe the CME-driven shocks will not accelerate near-relativistic electrons out of the ambient coronal plasma, but that a seed population of non-thermal electrons (e.g. a few keV) needs to be present before significant electrons are accelerated by the CME. The more energetic/intense the seed population, the more energetic/intense the subsequent event. Some very intense electron events, such as 20 February 1999, 18 February, 2000, and 12 July, 2000, occurred when the associated CME was the second of a pair, separated by only a few hours. It is possible that electrons trapped in the magnetic structure of the first CME cannot escape into the interplanetary medium, but populate the near-solar environment behind the first event and thus become available as a seed population for the second CME, and thereby produce an exceptionally intense event.

There are other puzzling features of the events which are worth exploring in more detail. (1) Why do the beams not themselves produce radio emission in the corona? A possible answer to this is that there is a finite risetime (>10 minutes) for the acceleration (see Fig. 1) such that the energy spectrum is always in quasi-equilibrium, and it never develops a significant “bump on the tail” which is necessary for the production of a type III burst. (2) Why are some beams associated with CMEs of low speeds whereas other CMEs with much higher speeds do not appear to produce them? The answer may lie in the physical conditions in the medium through which the CME propagates. If the local Alfvén velocity is low, either because of a low magnetic field or a high density, then the Mach number may be enough to form a shock even though the absolute CME speed is relatively low.

**CONCLUSIONS**

The new results from our recent study (Simnett et al., 2002) are the following:

1. There is a temporal delay between the electron injection and the CME launch time, which suggests that the CME drives the acceleration mechanism.

2. The correlations we have found between the CME velocity and the electron intensity and spectral index are consistent with the signatures of shock acceleration.

3. The conclusion is that CMEs drive the shocks that accelerate the electrons.

There is one further implication of these findings. If the acceleration is predominantly a velocity-dependent process there is no reason why ions should not be accelerated also. However, observationally ions are not typically seen to as high a velocity as electrons.

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