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The Production of Near-Relativistic Electrons by CME-Driven Shocks

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Abstract. The solar sources of near-relativistic (E >30 keV) electron events observed at 1 AU are poorly understood. In general, the solar injection times deduced from the observed 1 AU onset times and assumed 1.2 AU travel distances yield injection times about 10 minutes after the associated flare impulsive phases and type III radio burst times. One interpretation is that the apparent delays occur in the interplanetary medium, probably due to scattering of the electrons. If the injection times are delayed from the impulsive phases, the electron acceleration might take place in CME-driven shocks. Here a large number of electron events observed with the UC/Berkeley 3DP detector on the Wind spacecraft are compared with CMEs observed by the Lasco coronagraph on SOHO and with type II bursts observed by the 40 to 800 MHz radio receiver at the Astrophysikalisches Institut Potsdam (AIP) and by the 20 kHz to 14 MHz WAVES instrument on the Wind spacecraft. The acceleration of at least some of the electron events is not consistent with the shock hypothesis.

Keywords. Sun: coronal mass ejections (CMEs), Sun: particle emission, Sun: radio radiation, shock waves

1. Introduction

1.1. *Delayed Solar Injections of Near-Relativistic Electrons*

It has long been understood that bursts of 2 to $\geqslant 100$ keV electrons accelerated near the Sun and observed at 1 AU are nearly always accompanied by solar type III radio bursts (Lin (1985)). The velocity dispersion of the electron fluxes produces an instability which results in Langmuir waves that are converted into electromagnetic waves at the local electron plasma frequency and its second harmonic (Melrose (1985)). Observations of 326 $E > 2$ keV electron events in space during a 15-month period in 1978-79 on the ISEE-3 satellite seemed to confirm the result that the type III radio bursts are produced by 2 to $\geqslant 10$ keV electrons (Lin (1985)).

The early analysis of solar electron events observed near solar minimum during 1994-95 with the 3-D Plasma and Energetic Particle (3DP) experiment on the Wind spacecraft showed surprising differences from the previous ISEE-3 results. The predominately higher energies ($E > 30$ keV) of the Wind 3DP electron events allowed a more accurate determination of solar electron injection times based on plots of electron onset times at 1 AU versus v^{-1}, where v is the electron speed, and on an assumption that the first electrons arrive scatter-free. That analysis led to the unexpected result that many impulsive electron injections at the Sun occurred up to half an hour later than the onset of the accompanying type III burst. Krucker *et al.* (1999) found that injection times of 41 of 58 $E > 25$ keV 3DP electron events were delayed beyond the timing onset uncertainties of each electron event and coronal and/or interplanetary type III burst. Twelve low energy ($E \leqslant 25$ keV) electron events, on the other hand, were much better associated with type III burst times, and there were at least 2 cases of hybrid events with type III-related $E \leqslant 25$ keV electrons and $E \geqslant 25$ keV electrons showing the respective simultaneous and delayed release times.

The existence of delayed solar electron events was then confirmed by Haggerty & Roelof (2001, 2002) using observations of 79 impulsive $38 < E < 315$ keV electron events with the Electron, Proton, and Alpha Monitor (EPAM) on the ACE spacecraft. The electron injections of the 45 EPAM electron events with associated metric type III bursts were characterized by a median electron injection delay of 9.5 minutes. A similar result was found for the electron injection delays relative to the starts of other kinds of flare electromagnetic emission. The EPAM study was recently extended through March 2002 to include 113 electron events by Haggerty *et al.* (2003), who found a median delay of 13 minutes between the metric type III bursts and the electron injection times. Haggerty & Roelof (2002) argued that the correlations of $r \sim 0.5$ between the $38 < E < 62$ keV peak electron intensities and several flare radio and X-ray parameters provided evidence of only a loose relationship between the electron events and the accompanying flares.

1.2. *The Shock-Acceleration Interpretation*

The first attempts to explain the origins of the delayed electron events invoked shock acceleration. Krucker *et al.* (1999) considered the association of electron events with coronal waves observed in the Extreme Ultraviolet Imaging Telescope (EIT) on board the SOHO spacecraft (Thompson *et al.* (1998)). They suggested that fast moving wave fronts at high altitudes allowed a wave front to link the flare site to the magnetic connection point to the Earth. Haggerty & Roelof (2001, 2002) suggested that the ~ 10 minute injection delay corresponds to the time for a shock forming in the low corona and propagating at 1000 km s^{-1} to reach 1 $R_\odot$, at which point electrons could be accelerated to near-relativistic energies by the shock and reach open field lines. Mann *et al.* (2003) found a local minimum of the Alfvén speed in the middle corona, i.e., 1.2–1.8 $R_\odot$, and a broad maximum around 2–6 $R_\odot$ (see Fig. 6 in Mann *et al.* (2003)). Since shocks form more easily in regions with low Alfvén speed, a disturbance would need a period to travel from the flare or CME source site up to the local minimum Alfvén speed, where shock acceleration of electrons could occur. That would lead to a delay between the flare peak time and the shock acceleration.

Simnett *et al.* (2002) tested this interpretation of delayed shock acceleration by comparing the injection times of impulsive electrons with the launch times of associated coronal mass ejections (CMEs). For 47 EPAM electron events associated with CMEs the electron injections were typically delayed by ~ 20 minutes from the CME launch times. In addition, the peak electron intensities and energy spectra spanning ~ 40 to 300 keV were correlated with associated CME speeds. Their results were confirmed by the extended analysis of EPAM electron events by Haggerty *et al.* (2003). Simnett *et al.* (2002) suggested that most of the impulsive near-relativistic electrons were produced in shocks driven by CMEs and released into space when the CMEs reached heights of ~ 2 to 3 $R_\odot$ from Sun center. Note that Mann *et al.* (1999, 2003) argued for a global maximum of the Alfvén speed in just this region of the high corona.

A similar shock interpretation for the near-relativistic electron events was proposed by Klassen *et al.* (2002), who investigated four near-relativistic impulsive electron events. In each case herring-bone (HB) and shock-associated (SA) emission soon after the start of the type II burst indicated the release of $E < 30$ keV electrons, but the near-relativistic electrons were released later, at least 11 minutes after the start of the type II burst and with no corresponding radio signatures. In their view both groups of electrons were accelerated by the shock, but the near-relativistic population was injected when the associated type II shock and CME were 2 to 5 $R_\odot$ from Sun center.

1.3. *Alternatives to the Shock Interpretation for the Delayed Electron Onsets*

While the case for shocks as producers of the near-relativistic electrons has been made as described above, alternative interpretations for the delayed injections have been proposed. Pick *et al.* (2003) and Maia & Pick (2004) studied Nancay decametric array and radio heliograph (NRH) images associated with EPAM near-relativistic electron events with delays $>$ 5 min from type III bursts and argued that coronal radio brightenings, resulting from post-eruptive magnetic reconnection or from interactions between coronal structures and passing coronal waves or CME bow shocks, are the sources of the delayed electron injections. Classen *et al.* (2003) gave a similar interpretation to an electron event observed on 2002 June 2 by the 3DP instrument.

Further evidence against the shock interpretation comes from a statistical survey comparing 57 3DP near-relativistic electron events with Nancay radio data. Klein *et al.* (2003a) found that two thirds of those events showed some burst or enhancement of decimetric or metric radio emission in the western hemisphere and within the electron injection windows. Type II bursts were found in only a minority of the events with enhancements, and in those cases the brightenings occurred at coronal heights lower than the shock. In a different approach to the shock interpretation, Klein *et al.* (2003b) used X-ray observations of occulted flares with type II bursts to put upper limits on interplanetary electron fluxes produced in coronal shocks. They found that the numbers of near-relativistic electrons in large events are close to or exceed the upper limits of their analysis.

A very different interpretation of the delays was suggested by Cane (2003), who found that the inferred injection delay times correlated directly with the times for the radio-generating electrons to transit to 1 AU. In addition, a correlation of the delays was also found with the 1 AU ambient solar wind densities, supporting her conclusion that interaction effects in the interplanetary medium were the cause of the anomalous delays of the electron onsets.

1.4. *Open Questions about Impulsive Near-Relativistic Electron Injection*

Although inferred near-relativistic electron injection delays after the type III burst onsets are clearly established by two independent studies (Krucker *et al.* (1999), Haggerty & Roelof (2002)), the statistical studies have shown neither a bimodal distribution of events, with one group clearly temporally associated with the type III bursts and the other clearly delayed, nor a single group of event onsets distinctly delayed beyond the type III burst onsets. Krucker *et al.* (1999) distinguished two groups simply on the basis of the timing uncertainties of the type III bursts and of the electron injection onsets (their Figure 3), and Haggerty & Roelof (2002) only determined median values of the delays (their Figure 5). Maia & Pick (2004) selected 21 EPAM near-relativistic electron events for study and found two groups – 10 weak, short events with essentially no delays and 11 events with variable delays associated with solar radio-complex bursts. This may suggest two physically separate groups of near-relativistic electron events, but their sample was too small for a firm conclusion.

It is further puzzling that in all the impulsive near-relativistic electron events we find an associated type III burst (Haggerty & Roelof (2002)) which, at least for the delayed events, is presumed to have no direct relevance to the near-relativistic electron events. Since all the impulsive near-relativistic electron events are associated with decametric-hectometric (DH) type III bursts observed in the Wind WAVES experiment (Haggerty & Roelof (2002)), another major question is why the delayed electron injections do not also produce type III bursts.

The case for the shock origin for the near-relativistic impulsive electron events is not without problems, such as the association of the electron events with CME-driven shocks. Although Simnett *et al.* (2002) found that 47 of the 52 electron events of their sample could be associated with Lasco CMEs, a direct comparison of their electron event list with the CMEs listed at the web site of the SOHO Lasco CME catalog (http://cdaw.gsfc.nasa.gov/CME_list/) shows that 17 of the 52 (33%) electron events do not have associated CMEs within a reasonable ($\sim$ 1 hour) time preceding the event onset. In 14 cases Simnett *et al.* (2002) associated features they termed blobs and jets with the electron events, but the solar corona observed in Lasco movies allows many more dynamic features than only the CMEs to be identified. Some such features may indeed be associated with shocks, but Gopalswamy *et al.* (2001) found that only 6 of 101 fast ($v > 900$ km s^{-1}) CMEs associated with DH type II bursts were narrower than 60°. Thus the association of the blobs and jets with coronal shocks would appear doubtful. Further, Simnett *et al.* (2002) point out that about a third of their event-associated CMEs have speeds below 400 km s^{-1}, presumed to be generally too low to drive shocks.

A related question is the determination of the association of the impulsive electron events with metric and DH type II bursts as another way to test the validity of the shock acceleration hypothesis discussed in Section 1.2. The association of either metric or DH type II bursts with either the EPAM or the 3DP electron events has not been systematically examined. A low rate of type II burst associations would call into question the presence of the presumed basic acceleration mechanism. A high correlation with both shocks and CMEs would lend support to the shock hypothesis. Here we undertake a more comprehensive examination of the associations of near-relativistic electron events with type II bursts and CMEs.

2. Data Analysis

2.1. *Selection of the Impulsive Near-Relativistic Electron Events*

We will work with two combined sets of near-relativistic impulsive electron events. The first set consists of the list of event onset times observed in the EPAM instrument, given in Table 2 of Haggerty & Roelof (2002) and extended through the end of 2001 (D. Haggerty, private communication). The event selection criteria and a brief description of the instrument are given in Haggerty & Roelof (2002). Each of the two EPAM detectors measures electrons in the $\sim$ 40 to $\sim$ 315 keV range in four channels. From their list we select for analysis only those events observed in their third (103 to 175 keV) or fourth (175 to 315 keV) energy channels.

The second set of events are the 3DP impulsive electron events from the solid state telescope (SST) given at the web site http://sprg.ssl.berkeley.edu/˜bezerkly/all_events.htm. The event selection criteria and a brief description of the 3DP instrument and data reduction are given in Ergun *et al.* (1998) and in Krucker *et al.* (1999). We selected events from two previously posted lists: the period 15 November 1994 to 22 June 2001, and a second period coinciding with the observations by the Ramaty High Energy Solar Spectroscopic Imager (RHESSI) from February 2002 to October 2002. The lists gave the estimated injection times, qualitative assessments of the event data, and links to SST intensity plots and pitch-angle distributions (PADs). From those lists we eliminated the "poor" events and used the "mediocre" and "good" events for the analysis.

Table 1. Associations with EPAM and 3DP Events

Electron event	AIP Type II	WAVES II/IV	CMEs
EPAM	16 of 41	5 of 40	27 of 34
3DP	35 of 90	17 of 90	57 of 69
Total	37 of 100	17 of 99	63 of 79

For this study we also required that metric radiospectrographic observations from the Tremsdorf station (Mann *et al.* (1992)) of the AIP be available from about 1 hour before the electron injection time through the injection time. These observations are normally made in the 800 to 40 MHz range from about 0700 to 1500 UT. Finally, we require that Wind/WAVES 20 kHz to 14 MHz observations be available through the duration of the electron event, which eliminates a single EPAM event, although we include that event in the statistics of Section 2.2. With these requirements we have a total of 41 EPAM events and 90 3DP events, of which 31 events are common to both lists, leaving a total of 100 different events.

2.2. *The Associations Statistics*

We now proceed to compare the electron events with three different solar signatures of shock acceleration - metric type II bursts, DH type II bursts, and CMEs. We first consider the associations between the AIP metric type II bursts reported at the web site http://www.aip.de./People/AKlassen/ and the EPAM and 3DP electron events. For an association the type II burst times had to be within $\sim$ 15 minutes of the inferred electron injection time. We found that 16 of the 41 (39%) EPAM events and 35 of the 90 (39%) 3DP events were associated with reported AIP type II bursts. For the combined 100 different events, 37 were associated with metric type II bursts, as shown in Table 1. We then compared the electron events with listings of possible DH type II bursts observed by the Wind/WAVES instrument (Bougeret *et al.* (1995)), requiring the DH burst onset to be within about 1 hour of the electron injection time. There are only 17 DH type II bursts associated with the combined 99 electron events with simultaneous Wind/WAVES data coverage.

The last comparison is with Lasco CMEs listed at the Lasco CME catalog website at http://cdaw.gsfc.nasa.gov/CME_list/. Sixty three of the combined 79 electron events (80%) with Lasco observations were associated with CMEs with onsets within $\sim$ 20 minutes of the inferred injection times. This is somewhat larger than the 67% CME association rate for the Simnett *et al.* (2002) list of EPAM events we discussed above. We further ask how many of the 63 associated CMEs had observed widths $> 60°$ or speeds > 400 km s^{-1}, and hence were likely to be associated with interplanetary shocks. The result is that only 43 of the 79 electron events (54%) were associated with wide ($> 60°$) CMEs and only 52 of the 79 events (66%) with fast (> 400 km s^{-1}) CMEs.

Finally, we did a reverse association, starting with AIP type II bursts and the complete list of all beamed EPAM events and all listed 3DP electron events, and found that 17 of 245 (7%) type II bursts could be associated with an EPAM event and 41 of 214 (19%) type II bursts could be associated with a 3DP event. We attribute this lower number of EPAM associations to the fact that only about 30% of all EPAM electron events were selected as beamed events (Haggerty & Roelof (2002)).

3. Discussion

We have compared EPAM and 3DP near-relativistic electron events with metric type II bursts, DH type II bursts, and CMEs in an effort to determine whether the resulting associations support the conclusion of Simnett *et al.* (2002) that most of the near-relativistic electrons observed in impulsive events are accelerated at CME-driven shocks. The associations of the electron events with metric (37%) and DH (17%) type II burst shocks are not high, suggesting that most of the electron events do not originate in shocks. The 80% CME association is much higher, but our understanding that shocks are driven only by wide and fast CMEs suggests a more realistic result of $\sim$ 50% association of electron events with fast and wide CMEs. In particular, we find that 11 of the 63 associated CMEs have speeds < 400 km s^{-1}, a fraction lower than that of Simnett *et al.* (2002), who found 17 of their 47 CMEs to have such low speeds. The difference is probably due to the fact that Simnett *et al.* (2002) selected their events from the Haggerty & Roelof (2002) list of all EPAM events, which extended to the EPAM energy channels 2, 3, or 4, while we have limited our event selection to only those extending to the higher EPAM energy channels 3 or 4. Thus a higher CME association might be expected for our more energetic electron events. In both studies, however, the significant number of low-speed CME associations raises doubt about the CME-driven shock hypothesis for electron acceleration in those events.

We pointed out that only 37% of the selected near-relativistic electron events were associated with metric type II bursts. As in the case with CMEs, this association is higher than that reported by Simnett *et al.* (2002) (3 of their 52, or 6%) probably because we restricted our study to the most energetic electron events. The low inverse association of metric type II bursts with all observed electron events ($\sim$ 20%) shows that most type II bursts are not associated with observed electron events. However, Figure 2 of Haggerty & Roelof (2002) indicates that the electron events are observed only from a broad longitude range of $\sim 60°$ on the visible disk. Let us assume a uniform type II burst visibility over a 200° longitude range (Kahler *et al.* (1985), Cliver *et al.* (2004)). Then $\sim 200/60 \times 20\%=$ 67% of all type II bursts can be associated with near-relativistic electron events. We can compare this result with the case of solar energetic proton (SEP) events, for which shock acceleration is presumed to be the dominant acceleration mechanism. Cliver *et al.* (2004) compared SEP ($E \sim 20$ MeV) events and metric type II bursts favorably located in the western hemisphere and over a similar time interval. In that study 56% of the western hemisphere metric type II bursts were not associated with SEP events, but 82% of the western hemisphere SEP events were associated with metric type II bursts. Thus most SEP events (82%) *are* and most electron events (63%) *are not* associated with metric type II bursts, supporting a possible but weak connection between coronal shocks and near-relativistic electrons. The inverse case of the higher association of type II bursts with electron events ($\sim$ 67%) than with SEP events (56%) suggests a higher occurrence of electron events than of SEP events.

Pick *et al.* (2003) and Maia & Pick (2004) have divided EPAM near-relativistic electron events into two groups, one of which show essentially only type III radio bursts and no inferred injection delays from the type III bursts. The second group were associated with major changes in complex radio bursts which coincided with the inferred injection times that are delayed from the type III bursts; 6 of those events had metric type II bursts, and 5 did not. Maia & Pick (2004) argued that even when type II bursts were present, the shocks may have worked as restructuring agents rather than as direct accelerators of electrons. Our results are consistent with the conclusion that at least some, and perhaps a majority, of the near-relativistic electron events do not originate in CME-driven shocks.

However, a role for shock-accelerated electrons in broad, fast CMEs remains a viable concept.

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Discussion

TYLKA: This is really a question for David Ruffolo, who showed this morning that the time vs $1/\beta$ analysis may not be reliable for determining onsets, at least for ions. Might similar effects contribute to the delay here?

Kahler: The delays are comparable to the travel time. Ruffolo says he does not expect such large systematic errors in the velocity dispersion analysis.

Ruffolo: (to question of Tylka after talk of Kahler) Was the delay on the order of tens of minutes? (Kahler: Yes.) Then, no, I don't think a systematic error in the onset time vs. 1/v fit could account for that delay.

Schwenn: You told us what these relativistic electrons are not due to. So what are they due to, in your opinion, and why?

Kahler: At this time I favor the interpretation that the delays are due to propagation, but we can not rule out any of the several suggested scenarios.

Grechnev: What for the velocity did you use in your study? If it is the velocity from the SOHO/LASCO CME catalog, then the velocity of the shock can be a little bit different than the velocity of the frontal structures. This can change the selection which you had.

Kahler: I used the speed of the CME leading edge. You are right that the shock speed should be higher than the CME speed, but the shock speed should increase with the CME speed.

Gopalswamy: In a recent study (Gopalswamy *et al.* 2004, JGR) we found that the electron intensity in the 108 KeV channel correlated with flare peak intensity in X-rays better than it did with CME speed. Does this have any bearing on your result?

Kahler: That result would suggest that acceleration occurs in the flares rather than in shocks.