Solar Physics (2006) 237: 383–395
DOI: 10.1007/s11207-006-0002-z

THE ELECTRON ENERGY SPECTRUM FROM LARGE SOLAR FLARES

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(Received 1 June 2005; accepted 17 May 2006; Published online 27 August 2006)

Abstract. We report on the differential electron spectrum for intense transient events seen at one AU by the EPAM instrument on the *Advanced Composition Explorer* (ACE) spacecraft. Over an observing period from September 1997 to September 2005, there were 45 major events that could be reliably identified with a source flare on the Sun. In the ~40 – 300 keV energy range, the electron spectral index was between one and three for all but two of the events. Twenty-five of the events were associated with Geostationary Operational Environmental Satellites (GOES) X-ray class X flares. We compare this result with the spectral index measured from electron pulse events, lasting approx. one hour or less, where the spectral index is typically much softer than three. This suggests that the measured spectral index of near-relativistic electrons at one AU may be a reliable indicator of the source. We also examine the likelihood that fast coronal mass ejections (CMEs) are responsible in themselves for accelerating near-relativistic electrons and conclude that they do not.

1. Introduction

1.1. CATEGORIES OF ELECTRON SOURCE

Emission of non-thermal electrons (>40 keV) from the Sun is a relatively common occurrence. However, when such electrons are observed at one AU, they display a wide variation in spectrum, intensity, and anisotropy that reflects both the source at the Sun and the propagation in the interplanetary medium. Therefore, for any single observation, understanding the exact nature of the source is difficult and it behoves us to seek ways to clarify the situation. Because fast electrons are focussed in a diverging magnetic field, which typically is the situation in the interplanetary medium between the Sun and the Earth, then if the observer at one AU is magnetically connected to the source, the electrons will be seen as a collimated beam, moving outwards from the Sun. Thus, if we concentrate on beamed events, then one of the three variables is taken out of the uncertainty equation.

The energy spectrum may also provide some clue to understanding the provenance of electrons observed at one AU, and in this paper, we focus on the energy spectrum to gain further clarification of the solar electron source. Electromagnetic radiation at the time of flares indicates the presence of relativistic electrons on the low solar atmosphere. Typical proxies for such electrons are microwave radio emission, say at 15.4 GHz (a frequency that is monitored routinely), and continuum hard X-rays and gamma rays. Flares are routinely monitored by the Geostationary Operational Environmental Satellite (GOES) network and the largest events are the X-class flares, which typically show evidence for electrons of one MeV or higher. However, often there is no significant emission of electrons into the interplanetary medium from such flares, telling us that there is an acceleration mechanism/location for electrons which may efficiently contain the electrons at the Sun. It has been known for many years that the escaping fraction of the interacting energetic particle population is very variable (Ramaty and Murphy, 1987).

There is another source of electrons which comes from the high corona and may have no chromospheric signature. These events were first identified by Potter, Lin, and Anderson (1980) who showed that (a) the source was in the high corona above 0.5 $R_\odot$ and (b) they propagated through the interplanetary medium with little or no scattering. The events studied by Potter, Lin, and Anderson did not have detectable increases above 20 keV. However, Simnett (2005) has shown that occasionally such coronal events may extend to energies up to a few hundred kiloelectronvolts. The electron spectrum is usually characterised by a power law, $\mathrm{d}J/\mathrm{d}E \propto E^{-\gamma}$. However, one common characteristic of the coronal events is that the electron spectral index is steep, with γ ranging between 3.5 and 5 (Potter, Lin, and Anderson, 1980) and possibly even steeper at higher energies (Simnett, 2005a). These events are not associated with solar flares or CMEs.

A third source of electrons is that associated with CMEs. Simnett, Roelof, and Haggerty (2002) studied the association of beams of relativistic electrons, identified by Haggerty and Roelof (2002), with other solar activity and found that there was CME activity associated with 47 of the 52 events detected and suggested that the source was a CME-driven shock. Simnett (2005b) gave the spectral distribution for these events, which peaked at $\gamma = 3.5-4.0$, with the majority of the events in the region $\gamma = 2.5-5.0$.

Thus, we have three rather different physical processes occurring in the solar atmosphere which can produce electrons above 40 keV. This conclusion is reached through the careful isolation of events where we are sure that we are witnessing only one source. However, if we take an event at random, then we could be detecting electrons that come from any or all three sources. Lin (1985) showed electron energy spectra for various solar events, and some events (see Lin, 1985, Figure 12) have complex spectra, suggesting that there is more than one source. Thus, trying to unravel the complete picture is difficult. So far, the only way of determining the characteristics of the flare source is through indirect observations of the electromagnetic emissions, such as discussed above. In general, when electrons are observed in association with a major flare, there is also a fast CME and probably a contribution from the coronal source, too. However, if the flare source should have a characteristic spectral index that is different from that associated with the coronal source and CME-shock source, then by observing the electron spectrum, we would be able to distinguish the various contributions to a given event from the different sources. We suggest here that the best way to try to identify the spectral characteristics of the flare source alone is to select events with the highest electron intensities.

1.2. LARGE ELECTRON EVENTS

The purpose of this paper is to present the spectral analysis of the most intense interplanetary solar electron events from ~40 to 300 keV observed by the EPAM instrument on the ACE spacecraft (see below). From the above discussion, we believe a promising approach for trying to isolate the characteristics of the flare source is to select only the largest events in terms of peak intensity and fluence. It has been suggested (Simnett, 2005b) that the observations of the major flare event on 28 October 2003 were able, serendipitously, to distinguish all three discrete electron sources. In that event, the source attributed to the flare itself had the highest intensity and also exhibited a very hard (low γ) spectrum. This indicates that our approach of selecting the largest events for analysis may prove fruitful. The largest events are more likely to be dominated by a single source than the smaller events.

We shall show that the large electron events are typically associated with large GOES X-ray class flares and have differential energy spectra with an index $\gamma \ll$ three. The spectrum from coronal acceleration typically has $\gamma >$ four. We shall later discuss the spectrum from coronal mass ejections (CMEs) and conclude that it too is soft, with γ typically at least 3.5. Based on these studies, we suggest that the spectral index of observed solar electrons at 1 AU may be used as an indication of the source.

The outstanding question that the spectral determination may address is whether electrons generated in the chromosphere are injected into the erupting magnetic structure which is the CME, whence they may possibly be further accelerated at the CME-driven shock and/or trapped until the CME has reached open magnetic field lines. One well-established scenario is that the shock acceleration process works because downstream the particles are scattered by turbulence (*i.e.* on the sunward side of the CME), while upstream the particles are scattered off Alfvén waves (*i.e.* on the interplanetary side of the CME). Thus, the turbulence may be important for containing the flare electrons behind the CME. The fact that large flares often are accompanied by fast CMEs is addressed, as it is feasible that the intense events are all produced by CMEs. We will conclude, however, that this is unlikely.

2. The Observations

The electrons we discuss were detected by the EPAM instrument (Gold *et al.*, 1998) on the *Advanced Composition Explorer* (ACE) spacecraft, which is in interplanetary space near the L_1 Lagrangian point. Primarily, we use the data from magnetically deflected electrons, which are detected in four energy channels with boundaries

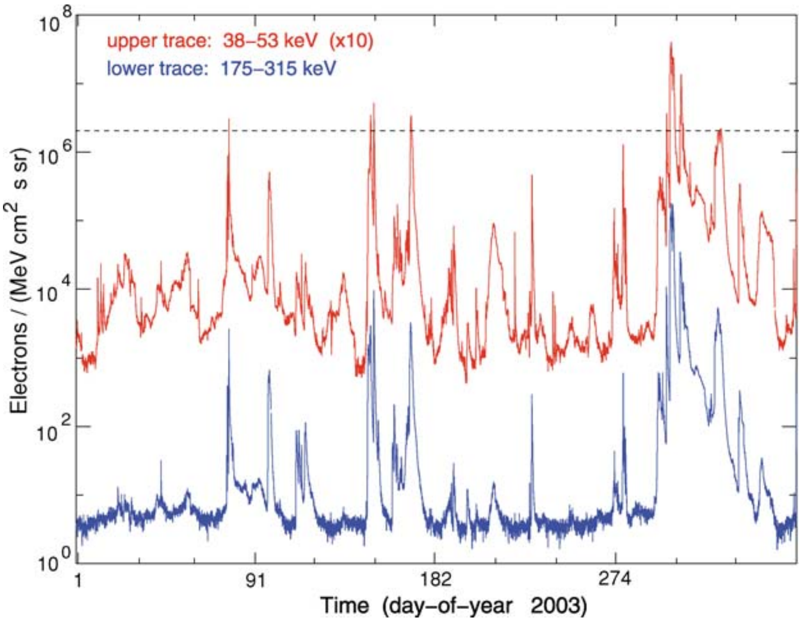

Figure 1. The 35 – 53 keV (*upper trace*) and 175 – 315 keV (*lower trace*) electron intensity at the ACE spacecraft in 2003. The data are spin- and one hour averages. The 38 – 53 keV intensity is multiplied by ten, and the dashed line is drawn at a true level of 2×10^5 electrons MeV^{-1} cm^{-2} s^{-1} sr^{-1}.

38 – 53 – 103 – 175 – 315 keV. The ACE spins every 12 seconds, and EPAM divides the measured deflected electron intensity into four 90° sectors. Figure 1 shows the 38 – 53 and 175 – 315 keV data from 2003 and it is clear that there are many events above background. Comparison of the two energy channels shows that the events often have very different energy spectra. The ACE was launched in August 1997 and we include in our analysis large events detected up to 12 September 2005. We define large events as those reaching above 2×10^5 electrons MeV^{-1} cm^{-2} s^{-1} sr^{-1} in the hourly and spin-averaged data. The intensity of the 38 – 53 keV electrons is plotted in Figure 1 at ten times the true intensity in order to avoid confusion, and the dashed line is our threshold for large events. The frequency of the large events is between three and ten per year, although in very active periods, it can be difficult to isolate each event, and a few events may have been missed for this reason.

We have also studied data from the LASCO coronagraphs (Brueckner *et al.*, 1995) on the SOHO spacecraft and the WAVES instrument (Bougeret *et al.*, 1995) on the WIND spacecraft. Finally, we have used ground-based data reported by Solar Geophysical Data (US Department of Commerce, Boulder, CO, USA).

The largest events typically follow major X-ray and Hα flares, and here we concentrate on the GOES soft X-ray classification as the X-ray record may include some events from just beyond the solar limb. The criterion for flare association

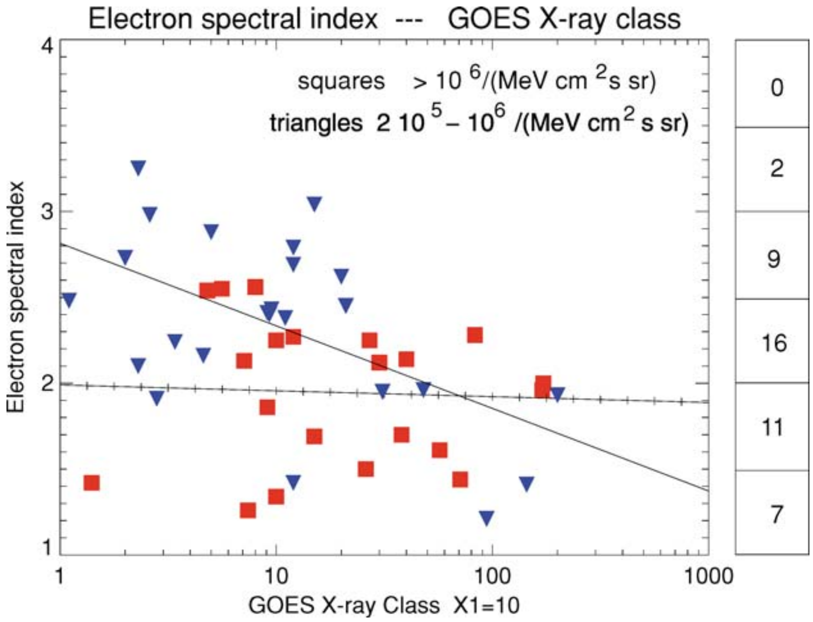

Figure 2. The distribution of electron spectral indices as a function of associated X-ray flare class. The *squares* represent the events with a maximum intensity (38 – 53 keV) above 10^6 electrons MeV^{-1} cm^{-2} s^{-1} sr^{-1} and the triangles are events where the maximum intensity is in the range $2 \times 10^5 - 10^6$ electrons MeV^{-1} cm^{-2} s^{-1} sr^{-1}. The *box* on the *right* contains the total number of events in each spectral index band, at 0.5 resolution. The *line* with *tick marks* is a least-squares fit to the *squares*, and the *line* without *tick marks* is a least-squares fit to the *triangles*.

is that the electron intensity at ACE should rise within an hour of the X-ray flare maximum. Using this criterion, events from flares well beyond the solar limb will not be included, nor the delayed events, which may appear to co-rotate with the Sun. Around ten large events could thus not be included in our study.

There were 45 electron events that had positive flare associations, and Figure 2 shows the electron spectral index plotted against the X-ray classification. In some events, the spectral index was not constant; in this case, we have taken the hardest spectrum. However, we have carefully avoided confusion with possible effects of velocity dispersion. Typically, the spectral determinations were taken following the maximum intensity in the 38 – 53 keV electron channel and also where the intensity was approximately constant and isotropic. Out of the 45 events, 8 were associated with flares in the eastern hemisphere.

In Figure 2, we have distinguished between events with a peak intensity (38 – 53 keV) above 10^6 electrons MeV cm^{-2} s^{-1} sr^{-1} (21 events, plotted as squares) and those between $2 \times 10^5 - 10^6$ electrons MeV^{-1}cm^{-2} s^{-1} sr^{-1} (24 events, plotted as triangles). There are 25 X-class flares, 13 “squares”, and 12 “triangles”. However, three events (M9.1, M7.4 and M1.4) were from flares believed to be behind the west limb, so these may well have been X-class flares if viewed from a different angle. In Figure 2, the M-class flares are between one and ten on the abscissa.

The straight line in Figure 2 is a least-squares fit to the complete data set. The line with tick marks is a least-squares fit to events with a peak intensity above 10^6 electrons $\mathrm{MeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$. The value of the spectral index is accurate to around ± 0.2.

The distribution of spectral indices from the large events not positively identified with a flare all fell within the distribution shown in Figure 2, with one exception (18 June 1999, $\gamma = 3.29$). In the box in the right of Figure 2 are the total number of flares in each spectral index interval, at a resolution of 0.5. The most probable spectral index from this distribution is around 2.2.

The majority of the large electron events were associated with large X-ray flares and also with fast CMEs. This is not surprising, as large flares tend to have high values in most studied parameters. Nevertheless, it is worth noting that of the 45 events studied, LASCO CME observations were available for 43, of which 33 events had speeds above $1000\,\mathrm{km\,s}^{-1}$, with 7 over $2000\,\mathrm{km\,s}^{-1}$.

3. Discussion

For this study, we have chosen all large events detected by ACE, as it is unlikely that two separate sources would contribute equally (Occam's razor) and therefore in such events we are sampling the output from one acceleration, rather than a possible mixture. Accepting this as a working hypothesis, we then find overwhelmingly that these large events are well associated with X-class or high M-class X-ray flares. Thus, there is little doubt that the electrons are intimately associated with these flares.

3.1. COMPARISON WITH THE PULSED EVENTS ASSOCIATED WITH CMEs

Another identified electron source is that associated with CMEs (Simnett, Roelof, and Haggerty, 2002). There are of course CMEs at the times of most major flares, including all those shown in Figure 2 whenever there was data coverage from LASCO. However, there are other times when there is also intense electron activity associated with a CME but only a modest Hα flare, and events that have no association with flares or CMEs. An example of the latter is the event of 17 March 2003 shown in Figure 3 (left panel), where the peak intensity in the peak sector was 1.2×10^5 electrons $\mathrm{MeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$. Also shown are the events on 30 April 2001 and 29 June 1999 which have similar intensities in the peak sector.

The even on 17 March had no flare counterpart in Hα or X-rays and was not preceded by a CME. The April 30 event was associated with a GOES class C2.2 X-ray flare, no Hα flare, but a fast ($1300\,\mathrm{km\,s}^{-1}$) CME. The 29 June event was

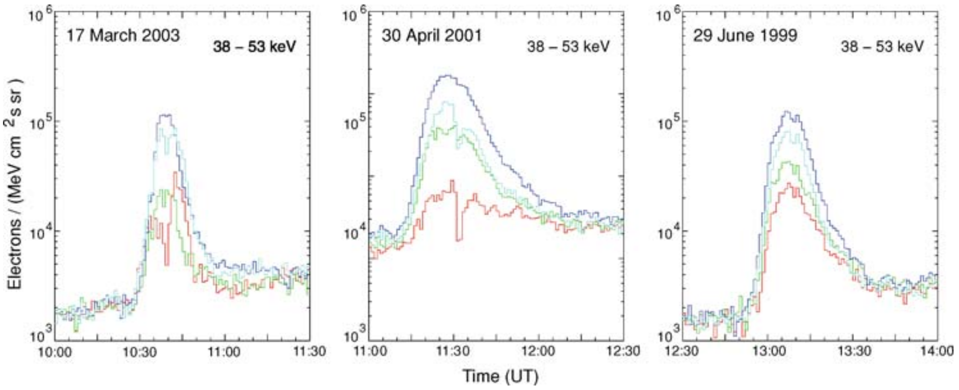

Figure 3. The intensity-time history of the electron pulse seen on 17 March 2003 around 10:30 UT (*left panel*); 30 April 2001 around 11:30 UT (*middle panel*); and 29 June 1999 around 13:00 UT (*right panel*). All four sectors of the 38 – 53 keV deflected electrons are plotted as one-minute averages.

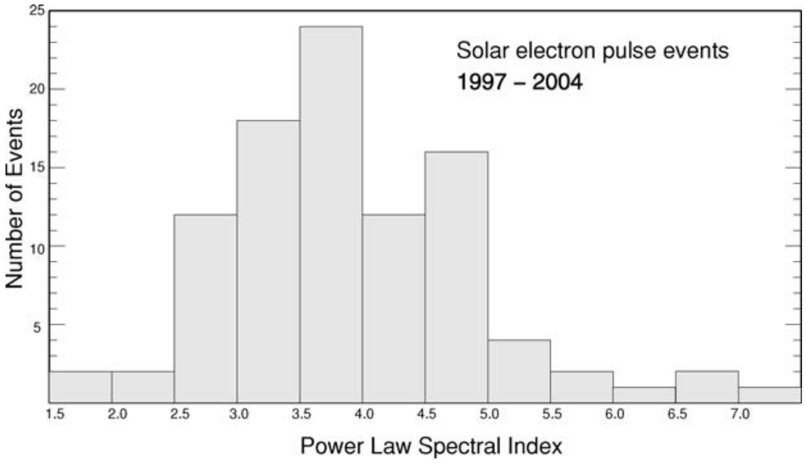

Figure 4. The distribution of electron spectral indices for short pulses of solar electrons.

associated with a C2.8 X-ray flare and an Hα flare, but the only CME association was with a small jet moving around 480 km s^{-1}. The point we wish to make here is that the short electron pulses are frequently, but not necessarily, associated with CMEs and X-ray flares, despite having peak intensities comparable with those from many major flares.

We have evaluated the electron spectrum at the peak of all the beamed electron events seen at ACE, with the selection criterion that the period between the onset and the time at which the intensity had dropped to one-third of the maximum should not be more than one hour. We refer to such events as pulses. From launch until the end of 2004, there were 96 events satisfying the selection criterion and the distribution of their spectral indices is shown in Figure 4.

The first thing to note from Figure 4 is that the distribution is wide and that the most probable index is between 3.5 and 4.0. There is a slight correlation between spectral hardness and peak intensity; however, the spectral indices for the events shown in Figure 3, which are amongst the most intense pulses observed, are 3.19, 4.80, and 4.17, respectively. Typically, the pulsed events are not associated with large flares. However, these events are both short and anisotropic, so on both counts they are unlikely to be included in the data set plotted in Figure 1, which was based on hourly and spin-averaged data. The only common event is that from the X17 flare on 28 October 2003, when the initial pulse was clearly separated from the later arriving flare particles, which had a completely different spectral index (Simnett, 2005b).

It is events such as 28 October 2003 that provide a clue as to the interpretation of the spectral distributions shown in Figures 2 and 4. In this event, there was both a pulse and a long-lived increase. If these are from different accelerations, one linked to the chromospheric flare and the other to the CME-driven shock, then it is probably fortuitous that in this event they can be separated. We would argue that in general the two sources are mixed by the time the electrons reach one AU. If the relative intensity of each source is regarded as a free parameter, then the spectrum in general will reflect this mixture. We suggest the data presented here supports the following hypothesis. Large X-ray flares indicate the presence in the lower solar atmosphere of electrons which typically have a hard spectrum, *i.e.* low value of γ. The escape efficiency of these "flare" electrons into the interplanetary medium, with good magnetic connection to ACE, may vary from high to virtually zero. However, electrons accelerated by the CME-driven shock, we surmise, typically have a soft spectrum. These may be detected as the sole component, in which case the measured spectral index is also soft, or they may be mixed with hard flare electrons, which would lead to a measured spectrum of intermediate hardness, *e.g.* $\sim$3.0 – 3.5.

There is a further complication. It is quite feasible that in some events the CME-driven shock does not accelerate significant fluxes of electrons, but that flare electrons may be trapped behind it and could be injected as a pulse or pulses into the interplanetary medium as the CME moves out through the high corona. In this case, we could get a pulse with a very hard spectrum, but we would also predict that there had been an X-ray flare.

In Table I, we show some key parameters regarding the four pulses with hard spectra. They are all observed within minutes of the maximum of the indicated flare. Two of the X-ray flares were presumably from events beyond the west limb. The two hardest events were associated with fast CMEs. The event on 11 July 1998 occurred when LASCO was not observing. The event on 25 April 2002 occurred without an Hα flare or a CME. All four events had a plausible association with a GOES C-class X-ray flare and all events were preceded by an interplanetary type III radio burst.

TABLE I

Characteristics of the pulse events with hard spectra.

Date	Spectral index	X-ray flare GOES class	Hα flare Size, location	CME speed (km s^{-1})
11 July 1998	2.41	C4.3	SF N17W66	No data
18 February 2000	1.75	C1.4	SF S20W26	890
25 April 2002	2.29	C2.5	None	None
20 October 2002	1.84	C5.9	None	1011

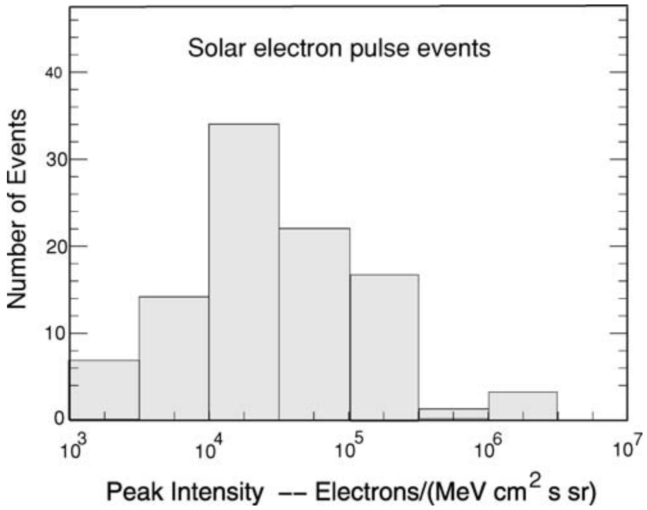

Figure 5. The distribution of 38 – 53 keV electron intensities for short pulses of solar electrons.

The pulse events, which we have identified overwhelmingly (but not exclusively) with CMEs, typically have much lower peak intensities than the large events shown in Figure 2. There is no overlap between the two sets of events as one of the criteria for event selection for inclusion in Figure 2 was a high intensity in the hourly and spin averaged data. As the pulses are short-lived beams, then this typically reduces the hourly and spin-averaged intensity considerably. In Figure 5, we plot a histogram of the peak intensity of the pulsed beams seen by ACE/EPAM. The intensity is the maximum value in the one-minute averaged data in the highest sector sampled by EPAM. It is clear that the pulsed events typically have lower peak intensities than those shown in Figure 2.

This is significant, for if fast CMEs were the main source of energetic electrons, then we would expect there to be more pulsed events at high peak intensities.

3.2. FAST CMEs WITHOUT ELECTRONS

It is generally accepted that fast CMEs, *e.g.* with speeds in excess of 1000 km s^{-1}, drive a shock, as this speed is well above the Alfvén speed in the corona (Mann *et al.*, 2003). If the presence of a strong shock is the primary requirement for electron acceleration, then we would expect all fast CMEs to be associated with electron events in the interplanetary medium. Given that a CME is not a very local phenomenon in the solar atmosphere, but typically has a wide angular extent, then if the fast CME is the primary accelerator, we would expect a fairly good correlation between such CMEs and electron events at ACE.

We have searched the LASCO data for 2000 and 2001 for fast CMEs with a plane-of-the-sky speed in excess of 990 km s^{-1}. We found 135 events, of which 59 were not accompanied by any electron increase at ACE. For 23 events, the interplanetary background electron intensity was high, which might have masked a new injection of electrons. Of the remaining 53 CMEs with electron increases, 10 were short spikes, while 43 were more substantial events. Thus, around half of the fast CMEs were not accompanied by any near-relativistic electron increase at ACE.

At first sight, this may not be too surprising, as LASCO responds to mass ejections from any position angle, although it is more sensitive to events moving off the solar limb. However, at least 33 of the 59 events with no electrons at ACE were accompanied by an X-ray or optical flare reported in Solar Geophysical Data, so this suggests that the CME in these cases had some component moving off the visible disc of the Sun, in which case, some intersection with magnetic field lines linking to ACE might be anticipated. Therefore, the lack of electrons from so many events would be surprising if the CME-driven shock was the primary electron accelerator.

The distribution of CMEs for the events with no electrons is worth examining. We first group the CMEs according to whether the event appears as a halo, virtually surrounding the LASCO occulting disc, or whether it is seen only off one side of the Sun. We further divide the CMEs into two groups according to the side of the Sun the brightest part of the event was seen, into categories West (W) or East (E). The results are shown in Table 2.

TABLE II

The number of fast CMEs with no electrons at ACE.

Halo		Non-halo	
W	E	W	E
5	6	19	29

As expected, the distribution is evenly balanced between West and East. Also, there are more events seen off the limb than as halos. However, there is a sufficiently large number of CMEs off the west limb (which typically has a good magnetic connection to the Earth) to show that a fast CME is not in itself responsible for accelerating and releasing near-relativistic electrons into the interplanetary medium. This point has been noted previously (Simnett, Roelof, and Haggerty, 2002).

3.3. TYPE II RADIO EVENT ASSOCIATION

We have examined, using Solar Geophysical Data, the type II radio burst association with the intense electron events seen at ACE and also the fast CMEs that were not accompanied by electrons at ACE. In the first group, 32 events have a metric type II burst, while 13 do not. Given that the events are typically associated with large flares, one would expect many of the events to be associated with any of the major flare phenomena – the big-flare syndrome. However, it is significant that over one-fourth of the large events are not associated with type II emission.

Of the fast CMEs that are not accompanied by detectable electron increases at ACE in 2000 – 2001, 58 events had no reported type II burst, while 8 did. Probably around half of these CMEs were propagating away from the Earth, in which case, any possible radio burst might not be detected. However, this is unlikely to be the dominant reason that no type II burst was observed for so many events.

The conclusions we draw from this is that fast CMEs do not drive type II events and that type II events are not the prime agents for energetic particle acceleration and injection into the interplanetary medium. For example, there was an X1.1 class flare on 2 April 2001 from N17W60 on the visible solar disc. It had a metric type II burst, a fast CME, yet there was no electron event at ACE. This event had a 15.4 GHz microwave burst at $710 \times 10^{22}\ \mathrm{W\,m^{-2}\,Hz^{-1}}$, so there was evidence for relativistic electrons at the flare site, which did not gain access to the interplanetary medium.

3.4. EVENTS WITH CONTRIBUTIONS FROM A CME AND A FLARE

The beamed pulse events by definition will tend to exclude events from significant flares, but if they are related to some form of CME, as suggested by Simnett, Roelof, and Haggerty (2002), then there will be many events which are a mixture of a pulse and a flare source. Figure 6 shows a small event that was detected by EPAM on 4 February 2004. The associated flare was GOES class C9.9 from S07W49 on the visible solar disc lasted 11 minutes and had its maximum phase at 11:18 UT. The electron onset (175 – 315 keV) was around 11:30 UT, so there is no doubt that the flare association is sound. LASCO observed a wide jet off the west limb with an extrapolated onset (at a nominal 1 $R_\odot$) at 11:05 UT. The speed in the plane of the sky was $518\ \mathrm{km\,s^{-1}}$.

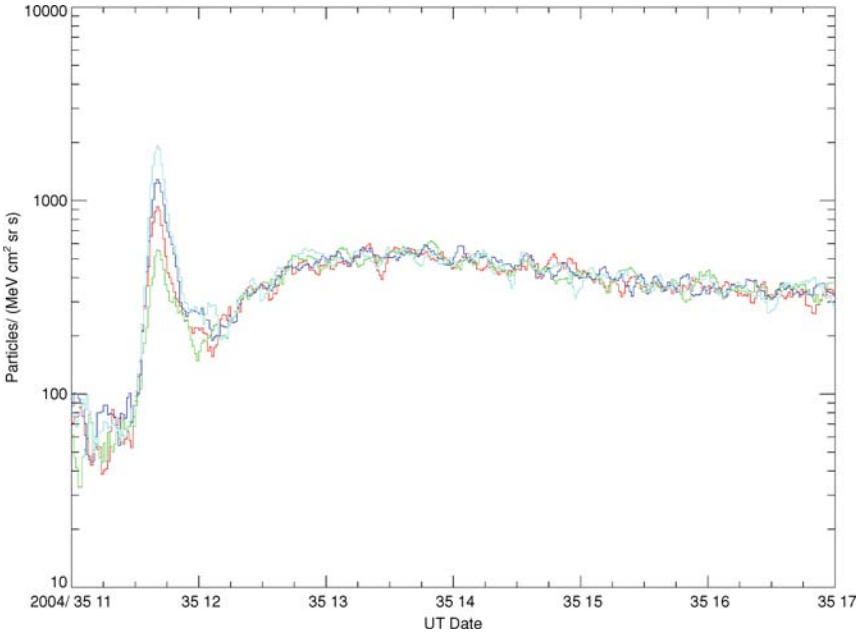

Figure 6. The 53 – 103 keV electron intensity-time history for an event on 4 February 2004. Each of the four sectors of the deflected electrons is shown. The data are three-minute averages, plotted every minute.

This event is clearly a combination of a beamed pulse, lasting around 20 minutes, and a more isotropic increase which had a broad intensity maximum around 14:00 UT. The energy spectrum in the peak sector of the pulse had $\gamma = 2.50$, while the spectrum of the main increase had $\gamma = 1.87$. Once the pulse has died away, we interpret the residual spectrum as representing flare electrons. Given that the spectrum at the time of the pulse probably is a mixture of the flare plus any contribution from the CME, it is likely that the spectrum of the pulse itself has a value near the centroid of the distribution shown in Figure 4. Thus, it is consistent with the hypothesis we are advancing in this paper. We suggest that many, if not most, of the electron events which are neither beamed pulses nor very large events are similar to that shown in Figure 6, with varying relative importance of the flare contribution and the CME contribution, folded in with the vagaries of propagation in the interplanetary medium.

4. Conclusions

The conclusion we reach from this study, together with that of Simnett (2005b), is that there are at least three distinct sources of solar electrons, each with a characteristic spectral range. The two we have discussed in this paper are the flare source, which typically has a spectrum between 1.5 and 2.5, and the beamed-electron pulses, which have much steeper spectra and a broader spectral distribution but with the most probable being between 3.5 and 4.0. The third source, namely coronal electrons, also has a soft spectrum, with $\gamma > 3.5$, and extending to over 5 (Lin, 1985; Potter, Lin, and Anderson, 1980; Simnett, 2005a,b).

The lack of electrons from such a large number of fast CMEs (Section 3.2) cannot, in our opinion, all be attributed to unfavourable propagation conditions. Therefore, we are forced to conclude that fast CMEs are not, in themselves, responsible for accelerating near-relativistic electrons. The events that are linked to CMEs must need a non-thermal seed population of electrons, which we tentatively identify with those producing the type III radio emission and may well be the part of the "coronal electron source" that is trapped in the corona. However, the spectrum from such events is characteristically soft. The events with high electron intensity and fluence are associated with major flares and have hard spectra. This should enable us to use the fact that events that have hard spectra are probably associated with flares, and, therefore, they may be separated from the other sources.

Acknowledgements

The author wishes to thank Dr E.C. Roelof for his useful insight regarding electron events. We are grateful to colleagues on the ACE and *Ulysses* teams for their help in making the data available and in a useable form. Starlink computing facilities were used for the detailed analysis.

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