

RELATIVE TIMING OF IMPULSIVE SOLAR ELECTRON INJECTIONS AND SOLAR ELECTROMAGNETIC EMISSIONS

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Abstract

The time histories of near-relativistic impulsive electron beam events (38–315 keV, $0.4 < v/c < 0.8$) measured at 1 AU by EPAM aboard ACE (Electron, Proton, and Alpha Monitor for the Advanced Composition Explorer) provide unique information on their Solar acceleration process. We have identified 79 such impulsive events at 1 AU from August 1997 through September 2000. The locations of the associated chromospheric $H\alpha$ emission show that the near-relativistic electrons are associated with western events. Detailed statistical analysis of the timing between the near-relativistic electron injection and the decametric type-III emission reveals that the electrons are injected after the electromagnetic (EM) emissions with a median delay of ~ 8 minutes. We find that the decametric type-III events have radial exciter speeds $\sim c/14$ (the velocity of a 1.3 keV electron). Therefore the electron populations escaping the corona at the time of the EM emission do not have a detectable near-relativistic component. The delayed injections of the 38–315 keV electrons are consistent with acceleration of the near-relativistic electrons by an out-going coronal shock ($v \sim 1000$ km/s) launched at the time of the prompt electromagnetic emissions.

1 Introduction

Reviews of the non-relativistic [Lin, 1974, 1985] and relativistic Solar electrons events [Simnett, 1974] conclude that the impulsive electron events observed in interplanetary space are only loosely coupled with $H\alpha$ flares, hard X-ray (HXR) events, microwave bursts, and even metric and decimetric type-III radio bursts. However, the type-III bursts are known to be produced by energetic electrons escaping the Sun. The lack of timing agreement between the bursts and the impulsive near-relativistic electron beams observed at 1 AU represents a significant observational and theoretical challenge.

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Adding to this challenge are a number of reports of an actual delay between Solar flare related electromagnetic emission and the most probable injection time of relativistic electrons [Simnett, 1974], as well as a delay between the injections of the non-relativistic and relativistic electron populations themselves [Lin, 1974]. In this study we report that the near-relativistic electron populations (38–315 keV) observed between 1997–2000 from the ACE spacecraft show a median ~ 8 minute delay between the decametric type-III bursts and the injection of the near-relativistic impulsive electron beam events.

2 Electron event list

From the launch of the ACE spacecraft (August 25, 1997) through September 9, 2000, two detectors of the EPAM instrument [Gold et al., 1998] measured 267 energetic electron events within annuli centered at $30^\circ \pm 25^\circ$ (DE30) and $60^\circ \pm 25^\circ$ (LEFS60) from the spacecraft spin axis. A minimum intensity of 10^3 particles/(cm²sr sec MeV) at 38–62 keV was required for the identification of the electron event onsets with sufficient statistical confidence. Analysis of these electron events at the highest temporal resolution show that many have nearly isotropic pitch angle distributions or non-dispersive spatial onsets. The remainder is composed of beaming distributions, with pitch angles highly collimated along the interplanetary magnetic field (IMF). With the goal of establishing the precise time that the near-relativistic electrons were injected into the heliosphere, only those events composed of beaming distributions with strong anisotropy were used because they are minimally affected by interplanetary propagation. From the initial 267 electron events, 79 (30%) were selected for this study based on the following two criteria.

Clear electron onsets: We define the onset time as the time when the electron intensity is first observed rising above the pre-event intensity. For our electron event list we used the time from the highest energy channel (i.e. highest velocity electrons) where a clear onset was observed.

Beaming distributions: A beaming distribution has a clearly anisotropic velocity distribution during the onset of the event while the direction of the peak electron intensity remains closely aligned with the IMF. As the energetic electrons are accelerated and released onto open interplanetary field lines and stream outward into the heliosphere, those particles whose pitch angles remain close to the IMF during their outward transit will be observed first at 1 AU. Thus, it is imperative that those electrons whose path is along the IMF are used to establish the onset time. The energetic electron pitch angle distributions (PAD) are used to determine which electron events show a beaming distribution, which detector system and direction (sector) measures the pitch angle most nearly parallel to the IMF, and therefore which system (LEFS60 or DE30) should be used to establish a precise electron injection time.

The electron event shown in Figure 1A is representative of the 79 events included in this study. The pre-event electron intensity has been subtracted to highlight the clear and prompt onset. Only the electron intensity in the beam direction is plotted. The times of maximum intensities at different energies show clear velocity dispersion. The electron intensities began rising sharply at 0930 UT with the E'4 channel reaching a peak

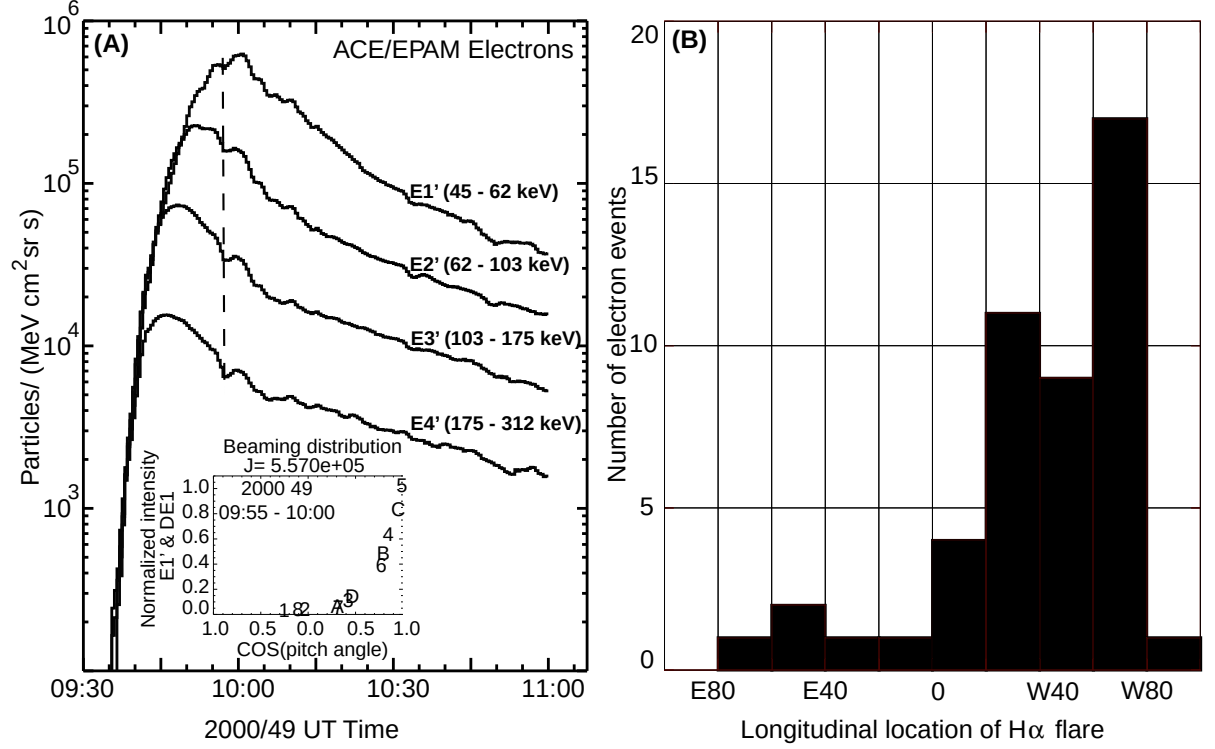


Figure 1: (A) Energetic near-relativistic impulsive beam-like electron event observed at 1 AU by ACE/EPAM showing a clear electron onset. This electron event is representative of the 79 beam like events used in this study. A five minute averaged electron pitch angle distribution is shown under the intensity curves in (A). Histogram (B) shows the longitudes of chromospheric $H\alpha$ flares associated with the near-relativistic electron beam events observed at 1 AU. The electron events we have selected are generally well connected to western longitudes.

intensity near 0945 UT and the lower energy E'1 channel reaching a peak near 1000 UT. A slight local interplanetary modulation is identifiable by an intensity fluctuation that is not dispersed in time; it is marked by a dashed line just before 1000 UT.

A five minute averaged electron pitch angle distribution (0.045–0.068 MeV) observed near the peak of the event is displayed under the intensity curves in Figure 1A. The pitch cosines are displayed on the abscissa and the intensity (normalized to the intensity in the peak sector) is plotted on the ordinate with the peak intensity in particles/(cm² sr sec MeV) indicated above the plot. The peak of the angular distribution is clearly seen in sector 5 which is near-parallel to the magnetic field. The sectorized angular distribution has a HWHM of $\sim 33^\circ$ (cosine = 0.83). This HWHM is comparable to the opening angle of the collimator (24°), so the actual beam is probably as narrow, or even narrower than the collimator itself.

While most escaping electron events observed at energies below ~ 20 keV are unassociated with chromospheric $H\alpha$ flares, Lin [1993] found $> 60\%$ of energetic electron events ($E > 15$ keV) have an associated $H\alpha$ flare. To verify that the electrons propagated directly along nominal spiral IMF lines once they were released into the interplanetary medium, we use the $H\alpha$ location as a proxy for the location from where the electrons were released

into the Solar wind. Figure 1B shows a histogram of the 47 electron events (60% of the total of 79) where an associated $H\alpha$ flare location was reported in the Solar–Geophysical data. During the vast majority of these events (37/47) the spacecraft was well connected to western longitudes (W30°–W80°).

3 Electron exciter radial velocities derived from decametric type–III bursts

It is known that electron beams create wave–wave interactions that then produce electromagnetic emission at the fundamental (f_{pe}) and/or second harmonic ($2 f_{pe}$). The WIND/WAVES experiment [Bougeret et al., 1995] provides measurements of the plasma emission associated with Solar type–III events in the frequency range from 14 MHz to below the nominal plasma frequency at 1 AU (20 kHz). These measurements allow the tracking of these drifting events from ~ 2 Solar radii to 1 astronomical unit (AU). In this study the highest resolution (16 seconds) WAVES data from the RAD2 receiver was used to identify the timing of electron beams in the high corona. The timing of type–III emission at a given frequency, coupled with the timing of the near–relativistic electrons observed at 1 AU, provides estimates of the relative timing between the type–III population and the injection of the near–relativistic population measured at 1 AU with an accuracy of a few minutes.

The radial exciter velocity of the electron beams responsible for the type–III radio emission can be determined by timing the emission at different frequencies (different heights in the corona). For a given event, the peak intensity of the type–III emission at different heights (frequencies) in the corona can therefore be determined to 16 seconds. Figure 2A shows an example of WAVES data with frequency cuts at 14 and 2 MHz. A clear ~ 90 second delay between peak emission at 14 MHz and 2 MHz is obtained.

In our study of 79 near–relativistic electron events observed at 1 AU we found a one–to–one correlation with the WAVES decametric type–III bursts. The procedure described by Figure 2A was applied to each of the type–III events associated with the 1 AU energetic electron events to determine the range of exciter speeds. Figure 2B shows a histogram of time delays between peak frequencies at 14 MHz and 2 MHz. Consistent with the example described in Figure 2A, a median delay of 95 seconds exists for the 79 type–III events used in this survey. If we use the frequency–density relationship given by Leblanc et al. [1998], which was itself derived from WAVES observations of type–III bursts beginning at 14 MHz, we assign altitudes of $\sim 2 R_S$ to 14 MHz and $\sim 5 R_S$ to 2 MHz, then the radial speed of the type–III exciter is $\sim c/14$, implying that the minimum electron energy in the exciter front was on average ~ 1.3 keV. This result is consistent with emission at the fundamental [Dulk et al., 1998] and within the range of previous studies [Dulk et al., 1987].

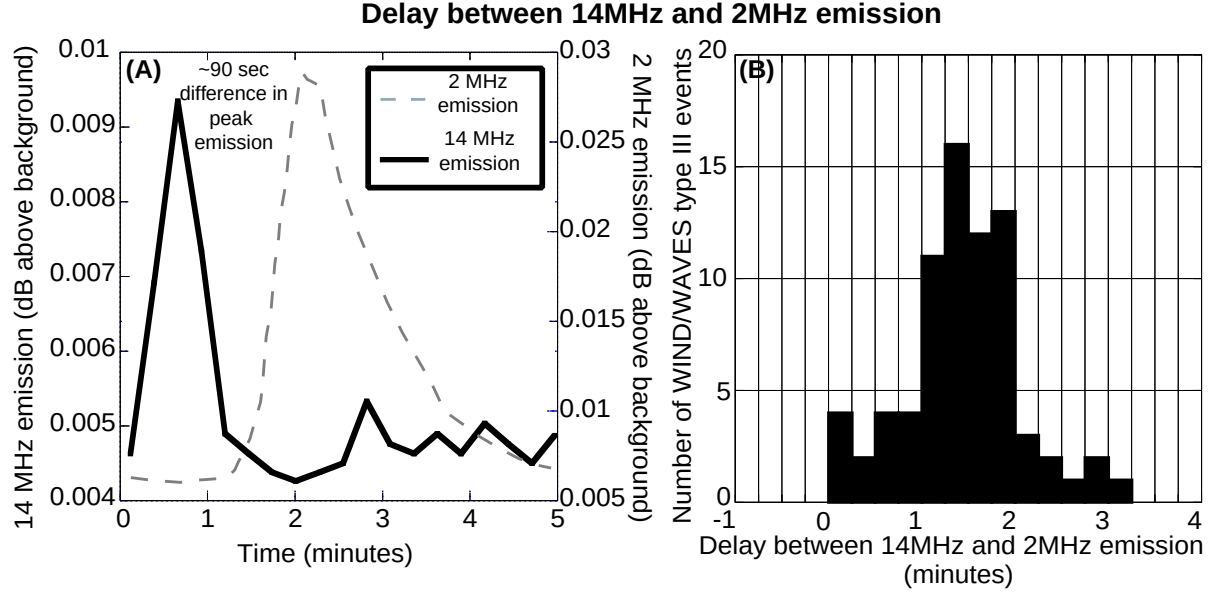


Figure 2: (A) Frequency cuts of the WIND/WAVES RAD2 intensities at 14 MHz (left axis), in dB above background, and 2 MHz (right axis) show a ~ 90 second delay between peak intensities. (B) Histogram of delay between frequency cuts at 14 MHz and 2 MHz associated with 79 near-relativistic electron events observed at 1 AU. The median ~ 95 second delay between emission at a coronal height difference of ~ 3 Solar radii roughly indicates a 1.3 keV exciter speed for those type-III events associated with impulsive beam-like electron events.

4 Correlations of near-relativistic electrons at 1 AU and decametric type-III events

Figure 3AB shows a representative event that compares the electron intensities (A) at 235 keV to the type-III event (B) observed at WIND. The time scales in Figure 3AB have been shifted from their Earth-observed time to the time of Solar emission. The time scale for the 235 keV energetic electrons were taken back to the Solar injection time, an offset of 13.7 minutes, based on a mean velocity 0.7 c and a propagation distance of 1.2 AU. The time of the type-III radio burst was also taken back to the coronal emission with a 500 second offset for the EM propagation time. For the event 9 September 1998 a clear 8 minute delay is observed between the type-III radio emission and the injection of the near-relativistic electrons.

We have compared the time between the 14 MHz emission peak and the 2 MHz emission peak (both taken back to the Sun) with the near-relativistic electron injection time (also taken back to the Sun) for each of the 79 events. The histograms of Figure 3 show the time differences at 14 MHz (C) and 2 MHz (D). In Figure 3CD the time ($t=0$) corresponds to the EM emission time so the histogram (both times at the Sun), shows the delay in the release of the energetic electrons relative to that EM emission time. A clear delay between emission at 14 MHz (C) and electron injection time is observed with an median delay of 7.9 minutes. A clear delay is also observed when comparing the time of 2 MHz (D) emission and the energetic electron injection time with a median delay of 6.8 minutes

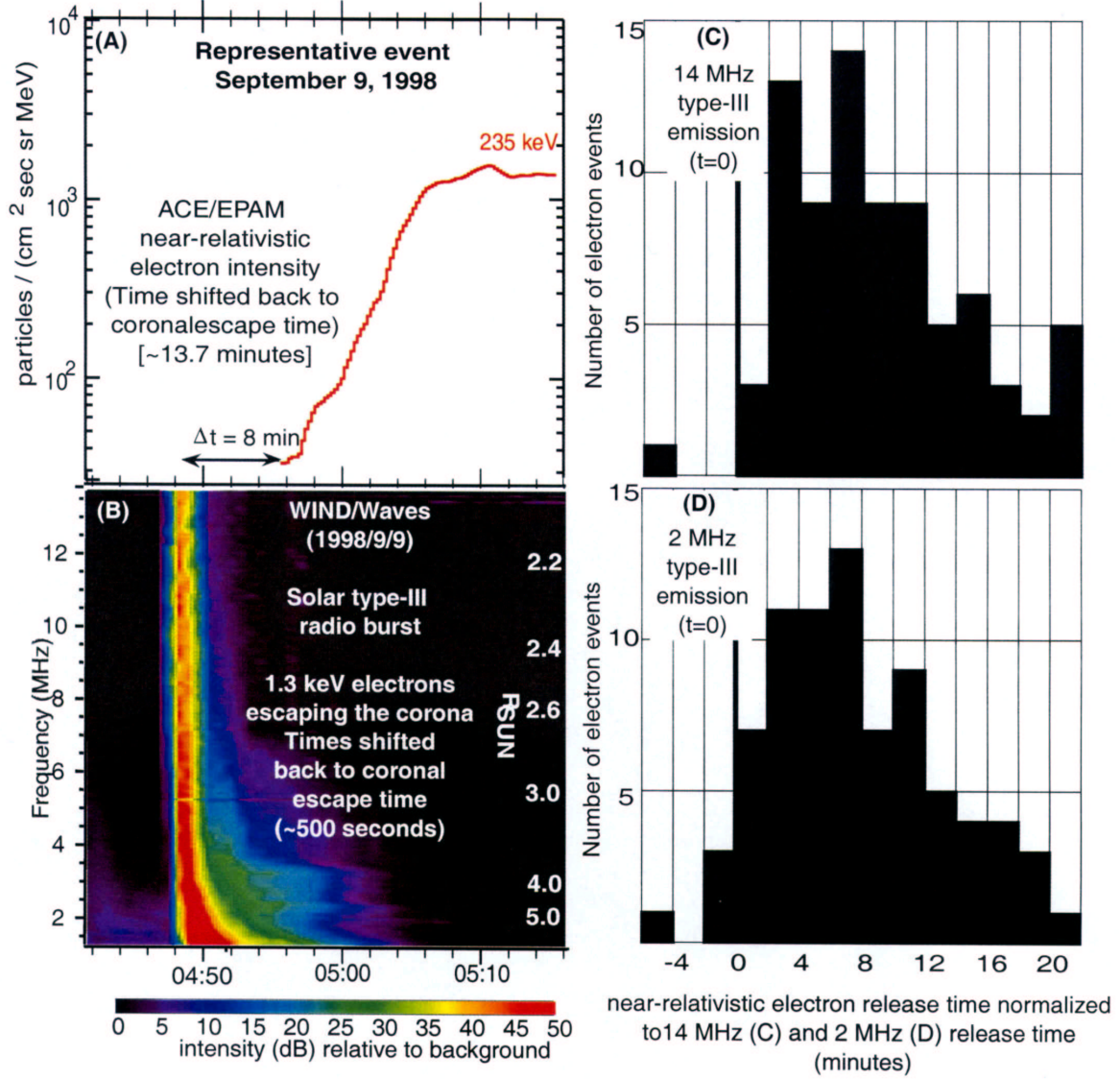


Figure 3: Representative event (left) showing association between type-III radio emission (B) with time taken back to coronal escape time (500 seconds) and a near-relativistic electron event (A) with time taken back to the Solar injection time ($v=0.7c$ and 1.2 AU propagation distance equates to 13.7 minute propagation time). A clear delay is observed between the type-III radio emission and the injection of the energetic electrons. Right histograms show the timing difference between type-III emission at 14 MHz (C) and 2 MHz (D) and the near-relativistic electron injection. The injection of the near-relativistic electrons are delayed relative to the 14 MHz type-III burst emission by a median of 7.9 minutes with a standard deviation of 5.6 minutes. The injection of the near-relativistic electrons are delayed relative to the 2 MHz type-III burst emission by an average of 6.8 minutes with a standard deviation of 5.6 minutes.

(consistent with the ~ 95 s delay between the 14 MHz and 2 MHz peaks in Figure 2.

5 Conclusion

Timing correlations between HXR events, microwave bursts, chromospheric H α flares, and metric type-III events have shown delays on the order of seconds or less. Studies of the so-called *second step* or *second phase* acceleration process found that the characteristic time for acceleration is on the order of the transit time of a shock through a Solar flare loop [Bai and Ramaty, 1979; Bai and Dennis, 1985], i.e. tens of seconds. The present study clearly shows that the delay between the injection of near-relativistic electrons and the decametric type-III emission is on the order of 8 minutes. Other studies have shown clear delays between the injection of the escaping near-relativistic electrons and microwave bursts, H α flares, SXR events, microwave bursts, as well as metric type-III events [Haggerty and Roelof, 2001]. Some early reports favored *storage effects* [Svestka, 1976] as a method to account for the delay observed in the relativistic electrons. Alternatively, Hudson et al. [1982] interpreted the 5–20 minute delays between various phases of a limb-occulted flare and electron injection as the time it took the acceleration agent to travel across the Solar disk from the flare site to the injection longitude of W 60°. Recently Krucker et al. [1999] reported delays between energetic electron events observed at 1 AU and meter-wave type-III events and discussed the delay in the context of high altitude EIT waves traveling from the flare site to the escape region.

In this study we have examined 79 impulsive near-relativistic electron events, the majority of which originated between W30°–W80° where a good Solar connection and therefore no significant delays due to longitudinal or latitudinal propagation of either electrons or EIT waves would be expected. Nonetheless a median 8 minute delay is observed between decametric Solar radio bursts and the injection of the energetic electrons into the inner heliosphere. We also find for these events that the radial exciter speed for the decametric type-III bursts is $\sim c/14$ corresponding to an electron energy of ~ 1.3 keV. Because of the delay, we can see that there are no detectable near-relativistic electrons associated with the type-III exciter populations. We do not consider temporary storage and sudden release a viable explanation for all 79 of the near-relativistic electron events, because all the electron beam events show remarkably similar rise times (e-folding ~ 3 minutes). We therefore believe that the delay must be due to radial transport of the accelerating mechanism on the order of 8 minutes. A typical coronal shock (1000 km/sec) originating near the chromosphere and propagating radially upward through the Solar corona takes ~ 12 minutes to propagate 1 Solar radius. The prompt EM emission (including the decametric type-III bursts) would be associated with the energy input that launches the shock. The electrons would then be released at an altitude where the electron spectrum had been extended out to near-relativistic energies by the shock acceleration and where those electrons would have access to open field lines. We therefore conclude that the delayed injections of the 38–315 keV electrons are consistent with acceleration of the near-relativistic electrons by an out-going coronal shock ($v \sim 1000$ km/s) launched at the

time of the prompt electromagnetic emissions.

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