

# <sup>1</sup> Energy Dependence of SEP Electron and Proton <sup>2</sup> Onset Times

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3 **Abstract.** We study the large solar energetic particle (SEP) events that  
4 were detected by GOES in the  $> 10$  MeV energy channel during December  
5 2006 to March 2014. We derive and compare solar particle release (SPR) times  
6 for the 0.25–10.4 MeV electrons and 10–100 MeV protons for the 28 SEP events.  
7 In the study, the electron SPR times are derived with the time-shifting anal-  
8 ysis (TSA) and the proton SPR times are derived using both the TSA and  
9 the velocity dispersion analysis (VDA). Electron anisotropies are computed  
10 to evaluate the amount of scattering for the events under study. Our main  
11 results include: 1) near-relativistic electrons and high-energy protons are re-  
12 leased at the same time within 8 min for most (16 of 23) SEP events. 2) There  
13 exists a good correlation between electron and proton acceleration, peak in-  
14 tensity and intensity time profiles. 3) The TSA SPR times for 90.5 MeV and  
15 57.4 MeV protons have maximum errors of 6 min and 10 min compared to  
16 the proton VDA release times, respectively, while the maximum error for 15.4  
17 MeV protons can reach to 32 min. 4) For 7 low-intensity events of the 23,  
18 large delays occurred between 6.5 MeV electrons and 90.5 MeV protons rel-  
19 ative to 0.5 MeV electrons. Whether these delays are due to times needed  
20 for the evolving shock to be strengthened or due to particle transport effects  
21 remains unsolved.

## 1. Introduction

22 The origin of energetic particles accelerated in solar events is still an open question.  
23 While flares and shocks driven by coronal mass ejections (CMEs) are believed to be two  
24 sources of solar energetic particle (SEP) acceleration in impulsive and gradual SEP events  
25 respectively [e.g. *Reames, 1999*], it is not clear what the exact flare-related acceleration  
26 mechanism in the impulsive SEP events is or where the CME-driven shocks most efficiently  
27 accelerate particles and when the particles are released in gradual SEP events.

28 Electron release has been observed to temporally coincide with type III radio bursts at  
29 the Sun and traveling along open field lines into interplanetary space [see *Lin, 1985*]. Using  
30 observations of the Three-dimensional Plasma and Energetic Particles instrument [3DP;  
31 *Lin et al., 1995*] on the Wind spacecraft, *Wang et al. [2006]* studied three electron events  
32 and found two distinct injections of electrons: that of low-energy electrons at energies  $\sim$   
33 0.4 to 6–9 keV began 9.1 min before the type III radio burst and that of  $\sim$  13 to 300 keV  
34 electrons started 7.6 min after the type III burst. Delays of 10 min up to half an hour  
35 between electron release time at the Sun and solar electromagnetic emissions (EM) have  
36 been reported by other works [e.g. *Cliver et al., 1982; Kallenrode and Wibberenz, 1991;*  
37 *Krucker et al., 1999; Haggerty and Roelof, 2002*]. *Krucker et al. [1999]* showed evidence  
38 that some electron events are not related to type III bursts. They found that the electron  
39 events appeared to be related to the passage of large-scale coronal transient waves, also  
40 called EIT waves or Extreme Ultraviolet (EUV) waves [*Thompson et al., 1998, 2000*],  
41 over the footpoint of the field line connected to the spacecraft. Although the nature of  
42 EUV waves is still largely debated, past studies using low-cadence ultraviolet images ( $>12$

minutes) showed that EUV waves are correlated with CMEs rather than flares [*Plunkett et al.*, 1998; *Cliver et al.*, 1999]. Based on more recent three-dimensional stereoscopic analyses, the EUV waves are generally believed to be the imprint of the CME driven shock on solar surface [e.g. *Veronig et al.*, 2008; *Patsourakos et al.*, 2009].

Proton release is probably more complicated than electron release. *Krucker and Lin* [2000] studied the timing of proton onsets in the energy range from 30 keV to 6 MeV. They found that the release of the protons appears to be energy-dependent. The most energetic protons are possibly released simultaneously with the electrons while lower-energy protons are released  $\sim 0.5$  to 2 hrs later than electrons. They also found that protons with energies between 0.03 and 6 MeV are released high in the corona, around 1–10 Rs above the electrons. Their results are consistent with studies by *Kahler* [1994] and *Gopalswamy et al.* [2012] on the CME heights at the time of SEP release. *Kahler* [1994] analyzed  $> 10$  MeV proton events and found that the peak of the intensity profile for  $> 10$  MeV protons occurs when the associated CME reaches heights of 5–15 Rs. *Gopalswamy et al.* [2012] examined the onset times and release heights of energetic particles using the ground-level enhancement (GLE) events. They found an earlier release time and a lower release height of CMEs for this highly energetic subset of events.

Although both SEP solar particle release (SPR) times and EM onsets have been discussed at length in the past, comparison between electron release times and proton release times has been discussed only in a few papers [e.g. *Cliver et al.*, 1982; *Haggerty and Roelof*, 2009; *Kouloumvakos et al.*, 2015; *Kahler et al.*, 2003; *Posner*, 2007]. In *Posner* [2007]’s study, the author adopted the prevailing assumption of simultaneous release of electrons and protons, but he also pointed out that “release of protons before electrons (and vice

66 versa) is possible [E. Roelof, D. Haggerty, personal communication, 2006]”. Using a group  
67 of 32 historic GLE events, *Cliver et al.* [1982] found that delays of 10 minutes between  
68 100 keV and 1 MeV electron SPRs and  $\leq 5$  minute delays between 2 GeV proton and 1  
69 MeV electron SPRs. Delays of 10 to 50 minutes in the proton SPRs relative to metric  
70 type II onsets for well connected events were found in the smaller GLE events. *Kahler*  
71 *et al.* [2003] compared the onset of relativistic electrons and protons of GLEs from solar  
72 cycle 23. They found that half of GLE events the relativistic proton injection preceded  
73 that of electrons, however, the low intensity GLEs tend to have a later time for the proton  
74 injection. Recently, *Kouloumvakos et al.* [2015] compared the proton and electron release  
75 as inferred from VDA based on Wind/3DP and ERNE data, and found a 7-min average  
76 delay of near-relativistic electrons with respect to deka-MeV protons. *Haggerty and Roelof*  
77 [2009] studied 19 electron beam events using EPAM 38-315 keV data, and found that for  
78 11 of the 19 events the arrival of 50-100 MeV protons followed by electrons within  $\sim 3$   
79 min. On the other hand, the remaining 8 events show a broad 5-25 minute delays of the  
80 protons relative to the electron injections.

81 In this paper, we study large SEP events with a peak  $> 10$  MeV proton flux above  
82  $10 \text{ cm}^2 \text{sr}^{-1} \text{s}^{-1}$  as observed by GOES from October 2006 (the launch of the Solar and  
83 Terrestrial Relations Observatory (STEREO)) to March 2014. The proton SPR times  
84 at various energies from 10 MeV to 131 MeV are investigated and compared to the re-  
85 lease times of 0.25 MeV–10.4 MeV electrons and solar EM onsets. The exact time when  
86 energetic particles are first released at the Sun is crucial to understanding the particle  
87 acceleration and where it takes place. This is the first systematic study and comparison  
88 between electron and proton SPRs for large SEP events in the new STEREO era. The

89 paper aims to address the following key issues: 1) Are protons and electrons accelerated  
 90 by the same source and released simultaneously at the Sun? 2) What is the acceleration  
 91 time needed for protons and electrons to reach high energies and are the acceleration times  
 92 energy dependent?

## 2. Observations and Data Analysis

### 2.1. Event Selection

From October 2006 to March 2014, GOES have observed 35 large SEP events with peak intensity great than  $10 \text{ cm}^2 \text{sr}^{-1} \text{s}^{-1}$  in the  $> 10$  MeV proton channel ([http://cdaw.gsfc.nasa.gov/CME\\_list/sepe/](http://cdaw.gsfc.nasa.gov/CME_list/sepe/)). In this paper we selected 28 of the 35 SEP events and excluded 6 events where the Energetic and Relativistic Nuclei and Electron instrument (ERNE) measurements have a data gap and 1 event where only a mild flux enhancement ( $< 10\%$ ) was seen above the background level. When an SEP event has multiple-increases of flux we define the earliest rise as its onset time and count it as one event. We divide these 28 events into two groups: SOHO (the Solar and Heliospheric Observatory) SEP events and STEREO SEP events. By choosing the smallest connection angles (CA) between SEP solar locations and magnetic foot-points of each spacecraft, we define whether a SEP event is SOHO SEP or STEREO SEP. We compute the longitude of connection footpoint by assuming Parker spiral theory:

$$\phi_0 = D\Omega/V_{slw} + \phi, \quad (1)$$

where  $\phi$  and  $\phi_0$  are the spacecraft longitude and its solar connection footpoint longitude,  $D$  is the distance to the Sun,  $V_{slw}$  is the average in-situ solar wind speed observed by the spacecraft, and  $\Omega$  is the solar rotation rate based on a Sidereal rotation period of 24.47

days. CA is then given by:

$$CA = \phi_0 - \phi_{src}, \quad (2)$$

93 where  $\phi_{src}$  is the solar source longitude of SEPs. It should be noted that an average  
 94 spread of  $\sim 30^\circ$  between active regions and source surface connection footpoints has been  
 95 reported in previous statistical studies [e.g. *Nitta et al.*, 2006; *Wiedenbeck et al.*, 2013]  
 96 and an uncertainty of CA angles as large as  $20^\circ$  was found using various methods in *Lario*  
 97 *et al.* [2014].

98 The solar source locations were identified as the locations of associated flares or erup-  
 99 tive prominences in movies of EUV images by the Atmospheric Imaging Assembly [AIA;  
 100 *Lemen et al.*, 2012] on the *Solar Dynamics Observatory* (SDO) spacecraft and by the EUV  
 101 Imager [EUVI; *Wuelser et al.*, 2004; *Howard et al.*, 2008] on the STEREO spacecraft. Ad-  
 102 ditional information on the events has been extracted from the GOES flare list ([http://](http://www.lmsal.com/solarsoft/latest_events/)  
 103 [www.lmsal.com/solarsoft/latest\\_events/](http://www.lmsal.com/solarsoft/latest_events/)), the CDAW CME catalog ([http://](http://cdaw.gsfc.nasa.gov/CME_list)  
 104 [cdaw.gsfc.nasa.gov/CME\\_list](http://cdaw.gsfc.nasa.gov/CME_list)), and the type II radio burst lists compiled by the Wind  
 105 and STEREO data center ([http://ssed.gsfc.nasa.gov/waves/data\\_products.html](http://ssed.gsfc.nasa.gov/waves/data_products.html)),  
 106 and type III radio burst data (<http://cdaw.gsfc.nasa.gov/images/wind/waves/>).

107 In-situ observations including the Electron Proton and Helium Instrument [EPHIN;  
 108 *Müller-Mellin et al.*, 1995] and ERNE [*Torsti et al.*, 1995] on the SOHO spacecraft, and  
 109 the High Energy Telescope [HET; *von Rosenwinde et al.*, 2008], Low Energy Telescope  
 110 [LET; *Mewaldt et al.*, 2008], and the Solar Electron Proton Telescope [SEPT; *Müller-*  
 111 *Mellin et al.*, 2008] on the STEREO spacecraft are used for the determination of the SEP  
 112 onsets.

113 SOHO/ERNE covers the energy range from 1.58 to 131 MeV of protons by using two  
114 different sensors. The Low-Energy Detector (LED) operates in the range 1.58 MeV to 12.7  
115 MeV and the High-Energy Detector (HED) from 13.8 MeV to 131 MeV. We determined  
116 proton onset times of SOHO SEP events using SOHO/ERNE 1-minute averages in proton  
117 energy channels from 13.8 MeV to 131 MeV. We used only HED channels since the small  
118 geometric factor at the lowest energies yields a relatively high intensity at 1-count level,  
119 which make it difficult to determine the event onset time accurately [*Vainio et al.*, 2013].  
120 We used SOHO/EPHIN 1-minute averages in energy channels from 0.25 to 10.4 MeV to  
121 determine electron onset times. When EPHIN data were not available, we used instead  
122 1-minute averages of the 230–392 keV electron data from Wind/3DP or the 175–315  
123 keV electron data from the Electron, Proton, and Alpha Monitor [EPAM; *Gold et al.*,  
124 1998] on the *Advanced Composition Explorer* (ACE). For STEREO SEP events, we used  
125 STEREO/SEPT 1-minute averages (sun-direction) in the electron energy channel 0.255–  
126 0.295 MeV, STEREO/HET 1-minute averages in the electron channel 2.8–4 MeV and  
127 proton energy channels from 40 to 100 MeV, and LET 1-minute averages in proton energy  
128 channel 10–12 MeV to determine the onset times of electrons and protons. We did not  
129 use HET data in the proton channel 13.6–15.1 MeV due to its large data gaps in many  
130 events. Instead LET standard data in the proton energy channel 10–12 MeV was used.

131 To estimate the scattering effect of the first arriving particles, we compute the anisotropy  
132 of the electrons using Wind/3DP data for the SOHO events and SEPT data for the  
133 STEREO events. The anisotropy of the protons was not considered in this study due to  
134 the lack of data available in instruments including ERNE, EPHIN, and HET, instead we  
135 use the VDA to evaluate their scattering effects. Furthermore, note that SOHO rotates



136 180° every three months and the pointing direction of ERNE and EPHIN will change from  
137 being sunward along the nominal Parker spiral direction to being perpendicular to that.  
138 Thus it is likely that both ERNE and EPHIN will miss the first arriving particles when  
139 SOHO's roll angle is 180°. We estimate the uncertainty by comparing the EPHIN and  
140 ERNE data with the available Wind/3DP data or ACE/EPAM data.

141 Finally, SEP intensity measurements can suffer from contamination. Possible causes  
142 of contamination include 1) particle misidentification, e.g. the presence of electrons in  
143 the proton channels and 2) missing particle energy, e.g. high-energy protons (electrons)  
144 deposit only a fraction of the energy at the detector and thus are counted as low-energy  
145 protons (electrons). *Posner* [2007] analyzed extensively EPHIN electron and proton mea-  
146 surements and found that some contamination (see also *del Peral et al.* [2001]) and in-  
147 strument dead time problems exist during the main phase of the SEP event, but the onset  
148 time determination using EPHIN electron and proton measurements can be done reli-  
149 ably. *Haggerty and Roelof* [2002, 2003] used simulations to examine contamination in the  
150 ACE/EPAM electron channels and they concluded that while the effect can be significant  
151 in the lowest-energy channels (E'1 and E'2), it is negligible in the highest two channels E'3  
152 (102–175 keV) and E'4 (175–312 keV). Other contamination factors are X-rays which will  
153 increase COSTEP front detector count rate [*Posner, 2007; Klassen et al., 2005*]. In this  
154 study, we have excluded contaminations that may be caused by the X-ray or other particle  
155 energy misidentifications.

156 So far, no simulations have been conducted to evaluate contamination in ERNE data  
157 (Valtonen, personal communication) or reported for STEREO HET, LET and SEPT data.

158 Therefore, we used the SEP intensity data from their instrument websites as provided with  
159 no additional contamination corrections.

## 2.2. SEP Onset Time Determination

160 We used an intersection slope method to determine the onset times of first arriving  
161 particles. We first make linear fits for the background and increasing logarithmic fluxes  
162 of SEPs respectively and then take the intersection of the two lines as the onset time.  
163 The uncertainty of the intersection slope method was estimated by the earliest and latest  
164 possible onset times, which were determined by the intersection with the background level,  
165  $\pm 3\sigma / (\text{slope} - \text{error}_{\text{slope}})$ , similar to the method used in *Miteva et al.* [2014]. Figure 1 shows  
166 the procedure for (a) the 2011 August 8 SEP event and (b) the 2011 August 4 SEP event.  
167 The SEP event in (a) has a rapid increase of flux, allowing for an accurate determination  
168 of the onset times while the SEP intensity in (b) has a slow rise which caused a larger  
169 uncertainty, as indicated by the gray rectangle in the figure. The obtained uncertainties  
170 of the intersection slope method range from  $\pm 2$  min to 9 min for the 28 SEP events. A  
171 similar uncertainty of ten minutes has been reported in other studies using alternative  
172 methods [e.g. *Huttunen-Heikinmaa et al.*, 2005; *Vainio et al.*, 2013].

173 In general, the uncertainty of the intersection slope method itself (caused by the back-  
174 ground flux fluctuation) is relatively small when compared with the high background  
175 errors.

It is well known that if the background flux of an SEP event is too high, it will mask  
the real onset time of SEPs [e.g. *Lintunen and Vainio*, 2004; *Laitinen et al.*, 2010]. To  
illustrate the background effect on the onset time, we over-plotted two elevated onset  
levels (ratio of background level to peak flux) of  $\sim 5\%$  (orange dashed line) and  $\sim 8\%$

(blue dashed line) in Figure 1 (b). They introduced an error of  $\sim 23$  min and  $\sim 32$  min, respectively. The error caused by the high background can be estimated by:

$$ERR_{bg/v} = (Int_{ont1} - Int_{ont0})/slope_{fit} \quad (3)$$

176 where  $Int_{ont1}$  and  $Int_{ont0}$  are the logarithm of the SEP intensity at onset level 1 and  
 177 onset level 0 and  $slope_{fit}$  is the linear fit slope to the logarithm of the SEP intensity. In  
 178 this work, we used equation (3) to correct the background effect by choosing a normalized  
 179 onset level as 1% of maximum flux in all data set, where the maximum flux is defined as  
 180 the SEP prompt peak within 6 hours of the onset. Also, note that the data time averages  
 181 set a lower limit to the onset uncertainty. For example, in Figure 1 (b) we applied a 3-  
 182 point running smoothing average to the 1-minute intensity data to make the early rise of  
 183 the event more easy to see, which set a lower limit of 3 min for this case. The uncertainty  
 184 listed in Table 1 has a lower limit of time averages and upper limit of the background  
 185 errors and errors of contaminations. Note that, the first small flux increase in Figure 1  
 186 (a) was caused by X-ray contamination, we have included an uncertainty of  $\sim 12$  min as  
 187 a lower limit in Table 1.

### 2.3. Solar Particle Release Time Determination

To infer the electron and proton release time at the Sun, time-shifting analysis (TSA) and velocity dispersion analysis (VDA) are two commonly used methods in the past works [e.g. *Krucker et al.*, 1999; *Tylka et al.*, 2003; *Malandraki et al.*, 2012; *Vainio et al.*, 2013]. The TSA computes the SPR time by shifting the onset time by particle traveling time along the nominal Parker spiral field line:  $t_{SPR} = t_{onset} - l/v$ , where  $l$  is the nominal path length from the Sun to the spacecraft and  $v$  is the particle speed. The nominal path

length is computed using the Parker spiral field-line model with the average solar wind speed measured in-situ at the observing spacecraft. The result of TSA represents a latest possible release of SEP particles. It is a good approximation if the SEP particles travel nearly scatter free at nearly zero pitch angle along the magnetic field line. For those particles which experience strong scattering, the TSA method can introduce large errors, especially for the protons. The error of TSA SPRs is given by:

$$ERR_{tsa} = (l_{sct} - l_{nom})/v \quad (4)$$

188 where  $l_{sct}$  and  $l_{nom}$  are scattering path length and nominal path length and  $v$  is the particle  
 189 speed. Note that the TSA method is a good approximation for near-relativistic electrons  
 190 and the TSA error for electrons is relatively small due to their extremely high speeds. For  
 191 example, considering a path length range of 1.25 AU to 2 AU, the uncertainty of the TSA  
 192 is given by  $dt = (2AU - 1.25AU)/v$ . For 1 MeV and 0.25 MeV electrons and 100 MeV,  
 193 50 MeV and 10 MeV protons, the corresponding errors are  $\sim 6$  min, 8 min, 13 min, 19  
 194 min and 40 min.

195 The velocity dispersion analysis (VDA) is another method commonly used to estimate  
 196 the release time of SEPs and their travel path length. The VDA method is based on the  
 197 assumption that particles at all energies are released simultaneously and travel the same  
 198 path length [*Krucker et al.*, 1999; *Tylka et al.*, 2003; *Vainio et al.*, 2013].

199 The particle arrival time at 1 AU is given by:

$$t_{onset}(E) = t_0 + 8.33 \frac{min}{AU} L(E) \beta^{-1}(E) \quad (5)$$

200 where  $t_{onset}(E)$  is the onset time in minutes observed in different energy  $E$ ,  $t_0$  is the  
 201 release time in minutes at the Sun,  $L$  is the path length (AU) travelled by the particle  
 202 and  $\beta^{-1}(E) = c/v(E)$  is the inverse speed of the particles. If energetic particles travel the  
 203 same path length and are released at the same time then a linear dispersion relation can  
 204 be obtained by plotting particle onset times versus  $\beta^{-1}$ . The slope and intersection of the  
 205 linear fit yield the path length and the particle release time at the Sun, respectively.

### 3. Statistics and Analysis Results

#### 3.1. Event Catalog

206 Table 1 summarizes the timing of 28 selected SEP events and associated solar eruptions.  
 207 The first and second columns of the table list SEP event number and date. The numbers  
 208 1–17 denote 17 SOHO SEP events and the numbers S1–S11 denote 11 STEREO SEP  
 209 events. The third and fourth columns of the table show the release times of SEP electrons  
 210 with uncertainty in parentheses. e1 and e2 represent 0.25–0.7 MeV and 2.64–10.4 MeV  
 211 electrons for SOHO SEP events and 0.255–0.295 MeV and 2.8–4.0 MeV electrons for  
 212 STEREO SEP events. The fifth to seventh columns of the table show the release times of  
 213 SEP protons. p2, p1 and p0 represent 80.2–101 MeV, 50.8–67.3 MeV and 13.8–16.9 MeV  
 214 protons for SOHO SEP events and 60–100 MeV, 40–60 MeV, and 10–12 MeV protons for  
 215 STEREO SEP events. From the eighth to thirteenth columns are the onset times of type  
 216 III, metric type II, decameter-hectometric (DH) type II, CME speed and source location  
 217 and CME heights at the e1 release times. The fourteenth column denotes the observing  
 218 spacecraft and the fifteenth is the connection angle of SEP to the spacecraft.

219 In this work, we used the TSA method to infer particle release times and 8.33 minutes  
 220 have been added to the release times in order to directly compare with electromagnetic

221 emission onsets. Here the inferred SEP release times indicate when the particles are  
 222 injected onto the field line connecting to the observer. To avoid the large background  
 223 effect, we set the SPR time as null '—:—' when a onset level is greater than 10%.

### 3.2. Time Differences between Electron and Proton Release Times

224 Figure 2 shows histograms of time differences,  $dt$ , for the 17 SOHO SEP events between:  
 225 (a) e2 and e1 SPRs, (b) p2 and e1 SPRs, (c) p1 and e1 SPRs and (d) p0 and e1 SPRs,  
 226 where  $dt = t_{SPR}(e2, p2, p1, p0) - t_{SPR}(e1)$ , i.e.,  $dt$  is positive when the e2 and proton SPR  
 227 times are delayed from the e1 SPR times. In panel (a), the e2 release times are found to  
 228 be systematically larger than the e1 release times with an average of 6.8 min. 11 of the 12  
 229 events ( $\sim 91\%$ ) have  $dt < 10$  min and one event (event 6) has a delay of 14 min. In panel  
 230 (b), the p2 release times are delayed from the e1 release times with an average of 4.7 min.  
 231 10 out of 11 events ( $\sim 91\%$ ) have  $dt < 10$  min and one event (event 6) has a delay of 19  
 232 min. The p1–e1 SPRs in panel (c) show similar delays as the p2–e1 SPRs, ranging from  
 233 -3 min to 25 min, with an average of 5.2 min. For the p0 protons, 7 of 12 events ( $\sim 58\%$ )  
 234 have  $dt < 10$  min and five SEPs (event 3, 4, 6, 8 and 9) have large delays of  $\geq 10$  min.  
 235 Among these five SEPs, events 3, 6 and 8 are weak with small flux increases in e2 and p2.  
 236 Event 4 is associated with a high latitude source and events 4 and 9 shows a large proton  
 237 scattering effect(see Sections 3.5).

238 Figure 3 shows histograms of time differences,  $dt$ , for the 11 STEREO SEP events  
 239 between: (a) e2 and e1 SPRs, (b) p2 and e1 SPRs, (c) p1 and e1 SPRs and (d) p0 and e1  
 240 SPRs. Figure 3 displays a similar trend as Figure 2. Two events (event S5 and S10) in  
 241 the e2–e1 SPRs and three events (event S5, S6 and S9) in the p2–e1 SPRs show a large  
 242 delay of 12-28 min. Among these three events, S6 is associated with a low CME speed

243 with CA of  $4^\circ$  and S5 and S10 have no associated metric type II but DH type II bursts,  
 244 indicating a later shock formation time. For the p0 protons, 8 events present a broad  
 245 10-41 minute delay relative to the e1 release times, and 3 events (events S1, S4 and S8)  
 246 have  $dt < 10$  min. Among the 8 events with larger delays, 4 events (S2, S3, S9 and S11)  
 247 have experienced strong scattering effects (S7 has no data available for the VDA) and 3  
 248 events (S5, S6 and S10) have delayed proton release times.

249 We plot histograms of time differences,  $dt$ , between: (a) p2 and p1 SPRs, (b) p2 and  
 250 p0 SPRs and (c) p1 and p0 SPRs in Figure 4 (SOHO events) and Figure 5 (STEREO  
 251 events). Both Figure 4 and Figure 5 show that the p2 protons have similar release times  
 252 as the p1 protons with an average  $dt$  of  $\sim 2.5$  min and  $-0.2$  min. For the p0 protons,  
 253 there are 7 SOHO SEPs and 5 STEREO SEPs with delays of the p2-p0 SPRs within 5  
 254 min, two SOHO events 4 and 9 and four STEREO events S2, S3, S9 and S11 show proton  
 255 scattering effects, where p0 appeared to be released later than p2 and p1, i.e.,  $dt = p2-p0$   
 256 or p1-p0 is negative.

### 3.3. Time Differences between Electron Release Times and Radio Emission Onset Times

257 Figure 6 plots histograms of time delays between (a) e1 SPR times and type III onset  
 258 times, (b) e1 SPR times and metric type II onset times, and (c) e1 SPR times and DH  
 259 type II onsets. The e1 release times are found to be 2-42 min delayed from type III onset  
 260 times, and similarly 3-25 min from metric type II onset times. There are 5 events (1,7,11,  
 261 17 and S1) with delays  $< 5$  min and 7 events (4, 6, 12,13, 16, S3 and S7)) with delays  $>$   
 262 20 min. Most of events (59%, 16 of 27) have the delays ranging from 6-19 min. Among  
 263 the former 5 events (1,7,11,17 and S1), 4 of them are associated with metric type II burst

264 except S1, which has a DH type II detected 5 min later than the e1 SPR time. There are  
265 in total 7 events (see Figure 7) having no associated metric type II bursts but all of the  
266 28 SEP events are associated with DH type II bursts.

267 Figure 7 presents correlation of CAs and time differences, DT, between the e1 SPR  
268 times and metric type III onsets. Red, green and blue colors mark three groups with  
269 delays  $dt \leq 5$  min,  $5 < dt < 20$  min, and  $dt \geq 20$  min. From Figure 7, we can see  
270 that there is a poor correlation between CAs and DTs with correlation coefficient  $CC =$   
271  $0.167$  and the data points are widely spread in the whole plot. Event S8 has the second  
272 largest CA of  $-54^\circ$  but a relatively small delay of 16 min. This SEP event was associated  
273 with a M6.5 flare at N09E12. STB/HET, SOHO/EPHIN and ERNE, and GOES have all  
274 detected a rapid rise of SEP fluxes, despite of relatively large CA to STB ( $61^\circ$ ) and to  
275 SOHO ( $70^\circ$ ). This is one of the longitudinally wide-spread SEP events (Richardson et al,  
276 2014) and will be studied in our future work. On the other side, event 4 is the SEP event  
277 which has a small CA of  $2^\circ$  but a large delay, associated with a M3.7 flare at active region  
278 (AR) 11164 at N31W53. The type III onset, metric type II onset and the 0.25–0.7 MeV  
279 electron release time are 19:52 UT, 19:54 UT and 20:21 UT respectively. Although this  
280 is a well-connected SEP event to SOHO, there is a large delay of 24 min between the e1  
281 release and metric type II onset. A likely reason is that although this SEP event is well-  
282 connected to SOHO in longitude, however, its large source latitude (N31) and relatively  
283 small CME width kept it poorly-connected to the ecliptic plane [cf *Gopalswamy et al.*,  
284 2014].



### 3.4. SEP Electron Anisotropy

285 The TSA method assumes that the SEP particles have propagated scatter-free at zero  
 286 pitch angle along the magnetic field line, large errors may present in the TSA method  
 287 for events with strong scattering. To estimate the scattering effect of the first arriv-  
 288 ing particles, we compute the electron anisotropy using Wind/3DP data for the SOHO  
 289 events (we used ACE/EPAM electron data for events 1 and 2 when there was a data  
 290 gap in Wind/3DP) and SEPT data for the STEREO events. The solid state tele-  
 291 scope (SST) Foil pitch angle distributions (SFPD) for Wind 3DP electrons (available at  
 292 [ftp://cdaweb.gsfc.nasa.gov/pub/data/wind/3dp/3dp\\_sfpd/](ftp://cdaweb.gsfc.nasa.gov/pub/data/wind/3dp/3dp_sfpd/)) returns a velocity dis-  
 293 tributions function containing 7 energy bins from  $\sim 27$  keV to 520 keV and 8 pitch  
 294 angle bins roughly covering pitch angles from 0-180°. Note that the covered pitch-angles  
 295 can vary from distribution-to-distribution since the automated CDF routine tends to re-  
 296 move all the direct sun/anti-sun directions to avoid X-ray and EUV contamination (see  
 297 [http://cdaweb.gsfc.nasa.gov/misc/NotesW.html#WI\\_SFPD\\_3DP](http://cdaweb.gsfc.nasa.gov/misc/NotesW.html#WI_SFPD_3DP)). The SEPT instru-  
 298 ment provides 45–400 keV electron measurements. It consists of four identical telescopes  
 299 which cover four viewing directions: SUN (along the nominal Parker spiral to the Sun),  
 300 ANTI-SUN (away from the Sun), NORTH and SOUTH. In this Section, the anisotropy  
 301 of the protons are not computed due to the lack of anisotropy data in ERNE and HET.  
 302 Instead, we use the VDA to evaluate their scattering effects in Section 3.5.

303 The anisotropy of a SEP event is defined as

$$A = \frac{3 \int_{-1}^{+1} I(\mu) \cdot \mu \cdot d\mu}{\int_{-1}^{+1} I(\mu) \cdot d\mu} \quad (6)$$

304 where  $I(\mu)$  is the intensity at a given pitch-angle direction and  $\mu$  is the pitch angle con-  
305 sine. Omnidirectional intensities were calculated by integrating second-order polynomial  
306 fits to the pitch-angle distribution of intensities using 1-minute averages (12-second for  
307 Wind/3DP) of the data. To stabilize the fit during periods of poor pitch-angle coverage,  
308 an artificial point was added to the pitch-angle distribution to fill the uncovered range [cf  
309 *Dröge et al.*, 2014].

310 Figure 8 shows Wind 3DP SFPD measurements on the May 17 2012 SEP event, which  
311 serves as a good example of a strong anisotropic event. The upper panel shows the time  
312 series of the intensity in color coding as a function of pitch angle bins. The middle panel  
313 shows the 65 keV electron 8-bin intensity measured by the SST telescope. The third panel  
314 shows the anisotropy as computed from the pitch angle distribution measurements. The  
315 anisotropy reaches a maximum of 2.23 at 01:44 UT during the onset of this event.

316 In Table 2 column 2 we list the maximum anisotropy for the 27 SEP events (data  
317 are not available yet for the STEREO SEP event on 2014 February 25). The obtained  
318 anisotropies range from 0.27 to 2.97 (absolute values), which are similar to those computed  
319 from ACE/EPAM data in *Dresing et al.* [2014]. 6 out of 27 SEPs have relatively strong  
320 anisotropies with  $A > 2.0$ , 16 events have  $1.0 \geq A \leq 2.0$ , and 5 events have relatively weak  
321 anisotropies with  $A < 1.0$ . The obtained anisotropies suggest that most of electrons with  
322 finite pitch angles still experienced certain degree of scattering although the first-arriving  
323 electrons with  $\mu \sim 0$  are generally propagated with less scattering. The uncertainties of  
324 e2 and e1 brought by the scattering effects are 6 min and 8 min, respectively, for a path  
325 length of 2 AU.

### 3.5. The Proton VDA Release Time

326 In this section, we carry out the VDA to estimate the proton scattering effects and  
 327 compare the proton VDA release times with electron release times. The VDA analysis  
 328 was based on 1 min time resolution ERNE and HET (LET) proton data with energy  
 329 channels between 10 MeV and 100 MeV. The VDA onset times are determined based  
 330 on the fix onset level (see Figure 1) for all energy channels, which is selected to be the  
 331 minimum background level of all analysis channels. To avoid high-background effects or  
 332 errors brought by background variation, we have excluded the channels with background  
 333 levels  $> 10\%$  and channels with a slowly rising background (see details in Figure 9 and  
 334 Figure 10). In addition, to avoid energy-dependent scattering effect, we carried out the  
 335 VDA by using either high  $\sim 50\text{--}100$  MeV or low  $\sim 10\text{--}50$  MeV energy channels only,  
 336 depending on data availability. The energy range used in the analysis has been listed in  
 337 column 8 of Table 2 .

338 Figure 9 shows an example of SEP event on February 20 2014. The 2014 February 20  
 339 SEP is a strong anisotropic event with a maximum anisotropy  $A = 1.94$ . This SEP event  
 340 was associated with a M3.0 X-ray flare at S15W73 and a halo CME with speed of 948  
 341 km/s. The observed metric and DH Type II, and type III onsets are 07:45 UT and 08:06  
 342 UT, and 07:46 UT, respectively. The event CA is  $-24^\circ$  and GOES observed a small SEP  
 343 intensity of 22 pfu.

344 Figure 9 (a) plots the 12-second electron intensity in 27–520 keV energy channels from  
 345 Wind/3DP SFPD from the solar direction. A clear velocity dispersion in the peak flux is  
 346 visible. The velocity dispersion at the onset shows an instrumental effect: the intensity  
 347 at lower energy channels were contaminated by higher-energy channels. This occurred

348 when the high-energy electron lost only a fraction of its energy in the detector, a count  
349 at a lower energy was recorded resulting in too early onset times. The early onset effect  
350 at low energy can be more clearly seen in Figure 9 (b), where the electron time profiles  
351 have been shifted by the travel time of SEPs with 1.25 AU path length.

352 Figure 9 (c) plots the 1-minute proton intensity from ERNE, and (d) superimposed in-  
353 tensity profiles from Wind/3DP electrons, EPHIN electrons and ERNE protons on 2014  
354 February 20. For easy comparison, in Figure 9 (c) the intensity profiles have been nor-  
355 malized to the peak values and the travel times have been subtracted with 1.25 AU path  
356 length. The red vertical solid line in the figure indicates the type III burst onset time.  
357 Note that a slow rise of the background flux was shown in the 15.4 MeV proton channel  
358 before the sharp rising phase, to avoid the onset uncertainty, we have excluded this channel  
359 in the analysis based on onset levels less than 10% of the peak value (see Figure 10).

360 Figure 10 presents the VDA results based on onset times at 0.1%, 1%, 2%, 5% and 10%  
361 of the peak value. The results show that the first arriving protons at 0.1% onset level  
362 propagated nearly scatter-free with a path length of  $1.2 \pm 0.14$  AU. The later arriving  
363 protons at onset level  $> 5\%$  present a larger scattered path length with a path length of  $\sim$   
364 1.5 AU. However, although the scattered path lengths increase as the onset levels increase,  
365 the VDA proton release times remain roughly the same within 7 min of uncertainty. The  
366 TSA release time for 180 keV electrons from Wind/3DP is at 07:52 UT and for the e1 and  
367 e2 electrons from EPHIN are at 07:50 UT and 07:54 UT, thus no significant differences  
368 between proton and electron SPR times are found for this SEP event.

369 Caution has to be taken with the VDA due to high background effect and energy-  
370 dependent scattering effect. The energy-dependent scattering effect becomes more im-

371 portant for cases when there is a large amount of scattering. For such cases, the VDA  
 372 using the energy range from 10 to 100 MeV may yield a release time that is earlier than  
 373 expected [*Diaz*, 2011]. Figure 11 shows a good example of such a SEP event on 2012  
 374 January 27 which has a weakest anisotropy with  $A = 0.27$ . As shown in Figure 11, the  
 375 velocity dispersion onset times do not lie on a straight line but curved from high to low  
 376 energy, showing an increasing scattered path length. The VDA based on energy 15.4–36.4  
 377 MeV (green) yielded a path length of 2.51 AU, which is  $\sim 0.76$  AU larger than that in  
 378 57.4–90.5 MeV (blue); and the VDA using energy 15.4–90.5 MeV gave a too large path  
 379 length of 3.17 AU and a unreasonable release time that is earlier than the type III onset.

380 In Table 2, we list the VDA results along with the electron anisotropy, e1 SPR time,  
 381 e2 SPR time for the 28 SEP events. Entries with ‘—’ (5 of 28) are cases where the path  
 382 length values were outside the range of 1–3 AU due to high background level (HBG),  
 383 ion contamination (IC), or cases when data are not available (NA). The obtained proton  
 384 path lengths range from 1.18 to 2.51 AU. In general, the derived proton path length tend  
 385 to be larger for weak anisotropic events than strong anisotropic events. However, there  
 386 are cases with strong electron anisotropies show large apparent proton path lengths due  
 387 to the relatively high background levels (especially for the STEREO HET data). 15 out  
 388 of 23 events have the path lengths  $l \leq 1.5$  AU and 21 of 23 events have  $l \leq 1.65$  AU  
 389 except events 9 and S3, where event 9 (the January 27 2012 SEP event) has the weakest  
 390 anisotropy  $A = 0.27$ . By comparing the TSA release time with the derived release times  
 391 from the VDA, we obtain the maximum errors for the p2, p1, p0 protons of  $\sim 6$  min,  
 392 10 min and 32 min, respectively. The p2 TSA release times have the smallest error as  
 393 expected. The proton release times from VDA,  $t_{SPR}(p_{vda})$ , are found to be delayed from

394 the e1 SPRs by -1–30 min, and from the e2 SPRs by -9–18 min.  $\sim 70\%$  (16 of 23) events  
 395 have the  $dt_1 = t_{SPR}(p_{vda}) - t_{SPR}(e1) < 8$  min and seven events (3, 6,8,S5,S6,S9 and S10)  
 396 have  $dt_1 \geq 8$  min. 13 (out of 19) events have  $dt_2 = t_{SPR}(p_{vda}) - t_{SPR}(e2)$  within 6 min  
 397 and 3 events (S6, S9 and S10) have  $dt_2 > 9$  min. In addition, there are 3 events (1, 7 and  
 398 S2) having a negative  $dt_2$ , where events 1 and 7 suffered the X-ray contamination resulting  
 399 in a large uncertainty of  $\sim 10$  min in the e2 SPR times.

## 4. Summary and Discussion

### 4.1. Summary

400 By choosing the smallest CA among the three spacecraft, we derive and compare the  
 401 high energy electron and proton SPR times using SOHO/EPHIN electron fluxes in the  
 402 0.25–10.4 MeV channels, SOHO/ERNE proton fluxes in the 13.8–101 MeV channels, or  
 403 in the similar energy channels of the SEPT and HET (LET) detectors on STEREO. Our  
 404 main results are listed below.

- 405 • The e2 release times are found to be systematically larger than the e1 release times  
 406 by an average of 6.8 min and 7.3 min, for the 12 SOHO SEPs and 10 STEREO SEPs,  
 407 respectively. Among these 22 events, three events (6, S5, and S10) have a large 10–28 min  
 408 delay.

- 409 • The p2 protons are shown to have similar SPR times with the p1 protons. The  
 410 average delay between the p2–p1 SPRs are  $\sim 2.5$  min and -0.2 min, for the 12 SOHO  
 411 SEPs and 9 STEREO SEPs, respectively. For the p0 protons, there are 12 SEP events  
 412 showing small delays between the p2–p0 SPRs within 5 min and five events (9,S2, S3, S9  
 413 and S11) showing a large 10–32 min delay due to proton scattering effects.

414 • The proton VDA results show that protons are released simultaneously with the e1  
 415 electrons within 8 min for  $\sim 70\%$ (16 of 23) SEP events, and the e2 electrons with 6 min  
 416 for 13 of 19 events. There are  $\sim 30\%$ (7 of 23) SEP events showing a delayed proton release  
 417 time by  $\sim 8\text{--}31$  min. Among these 6 events, 3 events (6, S5, and S10) also have a large  
 418 e2-e1 SPR delay.

419 •  $\sim 65\%$  (15 of 23) protons events show a small scattered path length ( $< 1.5$  AU); 8  
 420 of 23 proton events have a large apparent path length ( $> 1.5$  AU), part of reason is due  
 421 to higher background levels in the STEREO HET data.

422 • The delays between e1 SPRs and type III onsets range from 2 min to 42 min. The  
 423 CME heights at the e1 release times range from 2.1 to 9.1 Rs. From the CME heights, it  
 424 is likely that the e1 electrons are accelerated by the CME-driven and/or flare shock waves  
 425 rather than flare reconnections.

## 4.2. Discussion

### 4.2.1. Association between Electrons and Protons

426 Our results are consistent with *Haggerty and Roelof* [2009]’s study, where they sug-  
 427 gested that near-relativistic electrons and the energetic protons are accelerated and released  
 428 by essentially the same mechanism(s). *Haggerty and Roelof* [2009] studied the injection  
 429 times of near-relativistic electrons and non-relativistic protons for 19 electron beam events  
 430 using ERNE 50-100 MeV proton and EPAM 38-315 keV electron data, and found that  
 431 11 of the 19 events (60%) are statistically consistent with zero delay between the proton  
 432 and electron injection within the uncertainty of  $\sim 3$ min. The remaining 8 events show  
 433 a broad 5-25 minute delays of the protons relative to the electron injections. They also  
 434 compared the peak intensity of 175–315 keV electrons with that of 1.8–4.7 MeV protons  
 435

436 from ACE/EPAM and found a good correlation in the peak intensity of electrons and  
437 protons.

438 Among the 28 SEP events under study, we found similar correlations between the peak  
439 intensity of e1 electrons and p0 protons, as shown in Figure 12. Furthermore, the profiles  
440 between different species are found to be very similar to each other although not identical,  
441 as shown in Figure 13.

442 Our results support the conclusion that near-relativistic electron and high-energetic  
443 proton acceleration are closely related to each other. On the other hand, how the inten-  
444 sity profiles evolve with time, which result from the transport-modulated SEP particle  
445 accelerations at an evolving CME-driven shock, is not well understood. For example, at  
446 the SEP rise phase, it is not well understood why the e2 electrons are the last to reach  
447 their peak value for event 1 (left in Figure 13); while in the second example (event 8, right  
448 panel in Figure 13), the e2 electrons reach the plateau before the protons.

#### 449 **4.2.2. Direct Shock Acceleration vs Transverse Transport**

450 Besides simultaneously released electron and proton events, there are seven events show-  
451 ing large delays of 8–31 min between proton release times  $t_{SPR}(p_{vda})$  from VDA and e1  
452 SPRs. These events are SEPs with small e2 and p2 intensities. Three possible reasons  
453 may account for these large delays: 1) the late formed shocks at high altitudes around DH  
454 type II onset times; 2) longer times needed for the evolving shocks to be intense enough  
455 to produce high-energy SEPs after DH type II onsets; 3) times needed for shocks in SEP  
456 events with large CAs to reach the magnetic connection footpoint to the observer. Among  
457 the above 7 events, events 8 and S6 have small CAs of  $6^\circ$  and  $3^\circ$ , events 3 and S5 have  
458 large CAs of  $30^\circ$  and  $32^\circ$ , and the other 3 events (3, 6, and S10) have intermediate CAs



459 of 13-21 °. 6 of these events have the similar e1 SPRs with the DH type II onsets within  
 460 5 min ( and a large 13-26 min delay between  $t_{SPR}(p_{vda})$  and metric type II onsets) except  
 461 event S10. The obtained timing comparing results are consistent with one (or two) of  
 462 the above three hypotheses. Rouillard et al. (2012) investigated the 2011 March 21 SEP  
 463 event using STEREO and SOHO observations. By tracking the CME shock lateral expan-  
 464 sion they demonstrated that the delayed solar particle release times are consistent with  
 465 the time required for the shock to propagate to the magnetic footpoint connecting to the  
 466 observer. On the other hand, for large CA and/or high latitude SEPs, an alternative (or  
 467 contributing) explanation is that the delay between the SEP release and electromagnetic  
 468 emissions is caused by the propagation times needed for the SEP particles to transport  
 469 across the field line to the connection footpoint of the observer [e.g. *Dresing et al.*, 2012;  
 470 *Qin et al.*, 2013; *Laitinen et al.*, 2015]. It is possible that both direct shock acceleration  
 471 and cross-field propagation of SEPs play roles in the formation of SEP intensity time  
 472 profile. At an evolving CME-driven shock near the Sun, many factors such as the shock  
 473 obliquity, the compression ratio and transport parameters may affect the SEP intensity,  
 474 further investigations are needed.

### 4.3. Conclusion

475 Our results suggest that near-relativistic electron and high-energy proton acceleration  
 476 are closely related to each other. There exists a good association between high-energy  
 477 electron and proton release time, intensity peak values and time profiles. For small in-  
 478 tensity SEP events, it takes longer times for the e2 and p2 to reach up to the detectable  
 479 flux levels. However, whether this delay is due to the times that needed for the evolving  
 480 shock to be strengthened or due to particle transport effects are not resolved.

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## References

Cliver, E. W., S. W. Kahler, M. A. Shea, and D. F. Smart (1982), Injection onsets of  
2 GeV protons, 1 MeV electrons, and 100 keV electrons in solar cosmic ray flares,  
*Astrophys. J.*, *260*, 362–370, doi:10.1086/160261.

- 502 Cliver, E. W., D. F. Webb, and R. A. Howard (1999), On the origin of solar metric type  
503 II bursts, *Solar Phys.*, *187*, 89–114, doi:10.1023/A:1005115119661.
- 504 del Peral, L., R. Gómez-Herrero, M. D. Rodríguez-Frías, J. Sequeiros, R. Müller-Mellin,  
505 H. Kunow, and H. Sierks (2001), Detection of Electrons with EPHIN, *International*  
506 *Cosmic Ray Conference*, *6*, 2263.
- 507 Diaz, I. (2011), Delay in Onset Times of Solar Energetic Particles, *International Cosmic*  
508 *Ray Conference*, *10*, 41, doi:10.7529/ICRC2011/V10/1068.
- 509 Dresing, N., R. Gómez-Herrero, A. Klassen, B. Heber, Y. Kartavykh, and W. Dröge  
510 (2012), The Large Longitudinal Spread of Solar Energetic Particles During the 17 Jan-  
511 uary 2010 Solar Event, *Solar Phys.*, *281*, 281–300, doi:10.1007/s11207-012-0049-y.
- 512 Dresing, N., R. Gómez-Herrero, B. Heber, A. Klassen, O. Malandraki, W. Dröge, and  
513 Y. Kartavykh (2014), Statistical survey of widely spread out solar electron events ob-  
514 served with STEREO and ACE with special attention to anisotropies, *Astron. Astro-*  
515 *phys.*, , *567*, A27, doi:10.1051/0004-6361/201423789.
- 516 Dröge, W., Y. Y. Kartavykh, N. Dresing, B. Heber, and A. Klassen (2014), Wide lon-  
517 gitudinal distribution of interplanetary electrons following the 7 February 2010 solar  
518 event: Observations and transport modeling, *Journal of Geophysical Research (Space*  
519 *Physics)*, *119*, 6074–6094, doi:10.1002/2014JA019933.
- 520 Gold, R. E., S. M. Krimigis, S. E. Hawkins, III, D. K. Haggerty, D. A. Lohr, E. Fiore,  
521 T. P. Armstrong, G. Holland, and L. J. Lanzerotti (1998), Electron, Proton, and Alpha  
522 Monitor on the Advanced Composition Explorer spacecraft, *Space Sci. Rev.*, *86*, 541–  
523 562, doi:10.1023/A:1005088115759.
- 524 Gopalswamy, N., H. Xie, S. Yashiro, S. Akiyama, P. Mäkelä, and I. G. Usoskin (2012),

- 525 Properties of Ground Level Enhancement Events and the Associated Solar Eruptions  
526 During Solar Cycle 23, *Space Sci. Rev.*, *171*, 23–60, doi:10.1007/s11214-012-9890-4.
- 527 Gopalswamy, N., H. Xie, S. Akiyama, P. A. Mäkelä, and S. Yashiro (2014), Major solar  
528 eruptions and high-energy particle events during solar cycle 24, *Earth, Planets, and*  
529 *Space*, *66*, 104, doi:10.1186/1880-5981-66-104.
- 530 Haggerty, D. K., and E. C. Roelof (2002), Impulsive Near-relativistic Solar Electron  
531 Events: Delayed Injection with Respect to Solar Electromagnetic Emission, *Astrophys.*  
532 *J.*, *579*, 841–853, doi:10.1086/342870.
- 533 Haggerty, D. K., and E. C. Roelof (2003), Electron scattering in solid state detec-  
534 tors: Geant 4 simulations, *Advances in Space Research*, *32*, 423–428, doi:10.1016/  
535 S0273-1177(03)90283-3.
- 536 Haggerty, D. K., and E. C. Roelof (2009), Probing SEP Acceleration Processes With Near-  
537 relativistic Electrons, in *American Institute of Physics Conference Series, American*  
538 *Institute of Physics Conference Series*, vol. 1183, edited by X. Ao and G. Z. R. Burrows,  
539 pp. 3–10, doi:10.1063/1.3266783.
- 540 Howard, R. A., et al. (2008), Sun Earth Connection Coronal and Heliospheric Investigation  
541 (SECCHI), *Space Sci. Rev.*, *136*, 67–115, doi:10.1007/s11214-008-9341-4.
- 542 Huttunen-Heikinmaa, K., E. Valtonen, and T. Laitinen (2005), Proton and helium release  
543 times in SEP events observed with SOHO/ERNE, *Astron. Astrophys.*, , *442*, 673–685,  
544 doi:10.1051/0004-6361:20042620.
- 545 Kahler, S. (1994), Injection profiles of solar energetic particles as functions of coronal  
546 mass ejection heights, *Astrophys. J.*, *428*, 837–842, doi:10.1086/174292.
- 547 Kahler, S. W., G. M. Simnett, and M. J. Reiner (2003), Onsets of Solar Cycle 23 Ground

548 Level Events as Probes of Solar Energetic Particle Injections at the Sun, *International*  
549 *Cosmic Ray Conference*, 6, 3415.

550 Kallenrode, M.-B., and G. Wibberenz (1991), Particle injection following solar flares on  
551 1980 May 28 and June 8 - Evidence for different injection time histories in impulsive  
552 and gradual events?, *Astrophys. J.*, 376, 787–796, doi:10.1086/170327.

553 Klassen, A., S. Krucker, H. Kunow, R. Müller-Mellin, R. Wimmer-Schweingruber,  
554 G. Mann, and A. Posner (2005), Solar energetic electrons related to the 28 Octo-  
555 ber 2003 flare, *Journal of Geophysical Research (Space Physics)*, 110, A09S04, doi:  
556 10.1029/2004JA010910.

557 Kouloumvakos, A., A. Nindos, E. Valtonen, C. E. Alissandrakis, O. Malandraki, P. Tsit-  
558 sipis, A. Kontogeorgos, X. Moussas, and A. Hillaris (2015), Properties of solar energetic  
559 particle events inferred from their associated radio emission, *Astron. Astrophys.*, 580,  
560 A80, doi:10.1051/0004-6361/201424397.

561 Krucker, S., and R. P. Lin (2000), Two Classes of Solar Proton Events Derived from Onset  
562 Time Analysis, *Astrophys. J.*, , 542, L61–L64, doi:10.1086/312922.

563 Krucker, S., D. E. Larson, R. P. Lin, and B. J. Thompson (1999), On the Origin of  
564 Impulsive Electron Events Observed at 1 AU, *Astrophys. J.*, 519, 864–875, doi:10.1086/  
565 307415.

566 Laitinen, T., K. Huttunen-Heikinmaa, and E. Valtonen (2010), On the Effect of Pre-  
567 event Background in Determining Solar Particle Event Onset, *Twelfth International*  
568 *Solar Wind Conference*, 1216, 249–252, doi:10.1063/1.3395847.

569 Laitinen, T., A. Kopp, F. Effenberger, S. Dalla, and M. S. Marsh (2015), Solar energetic  
570 particle access to distant longitudes through turbulent field-line meandering, *ArXiv*

571 *e-prints.*

572 Lario, D., N. E. Raouafi, R.-Y. Kwon, J. Zhang, R. Gómez-Herrero, N. Dresing, and  
573 P. Riley (2014), The Solar Energetic Particle Event on 2013 April 11: An Investigation of  
574 its Solar Origin and Longitudinal Spread, *Astrophys. J.*, *797*, 8, doi:10.1088/0004-637X/  
575 797/1/8.

576 Lemen, J. R., et al. (2012), The Atmospheric Imaging Assembly (AIA) on the Solar  
577 Dynamics Observatory (SDO), *Solar Phys.*, *275*, 17–40, doi:10.1007/s11207-011-9776-8.

578 Lin, R. P. (1985), Energetic solar electrons in the interplanetary medium, *Solar Phys.*,  
579 *100*, 537–561, doi:10.1007/BF00158444.

580 Lin, R. P., et al. (1995), A Three-Dimensional Plasma and Energetic Particle Investigation  
581 for the Wind Spacecraft, *Space Sci. Rev.*, *71*, 125–153, doi:10.1007/BF00751328.

582 Lintunen, J., and R. Vainio (2004), Solar energetic particle event onset as analyzed from  
583 simulated data, *Astron. Astrophys.*, , *420*, 343–350, doi:10.1051/0004-6361:20034247.

584 Malandraki, O. E., et al. (2012), Scientific Analysis within SEPServer - New Perspectives  
585 in Solar Energetic Particle Research: The Case Study of the 13 July 2005 Event, *Solar*  
586 *Phys.*, *281*, 333–352, doi:10.1007/s11207-012-0164-9.

587 Mewaldt, R. A., et al. (2008), The Low-Energy Telescope (LET) and SEP Central  
588 Electronics for the STEREO Mission, *Space Sci. Rev.*, *136*, 285–362, doi:10.1007/  
589 s11214-007-9288-x.

590 Miteva, R., K.-L. Klein, I. Kienreich, M. Temmer, A. Veronig, and O. E. Malandraki  
591 (2014), Solar Energetic Particles and Associated EIT Disturbances in Solar Cycle 23,  
592 *Solar Phys.*, *289*, 2601–2631, doi:10.1007/s11207-014-0499-5.

593 Müller-Mellin, R., et al. (1995), COSTEP - Comprehensive Suprathermal and Energetic

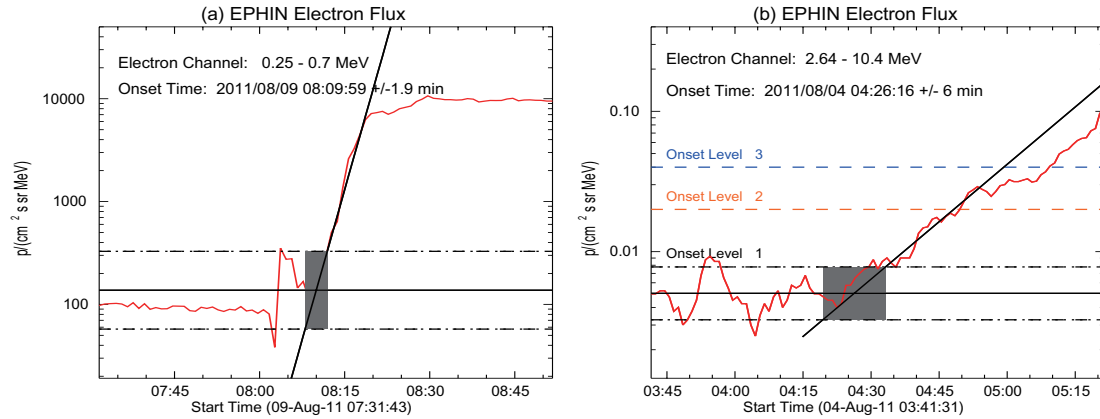
- 594 Particle Analyser, *Solar Phys.*, *162*, 483–504, doi:10.1007/BF00733437.
- 595 Müller-Mellin, R., S. Böttcher, J. Falenski, E. Rode, L. Duvet, T. Sanderson, B. Butler,  
596 B. Johlander, and H. Smit (2008), The Solar Electron and Proton Telescope for the  
597 STEREO Mission, *Space Sci. Rev.*, *136*, 363–389, doi:10.1007/s11214-007-9204-4.
- 598 Nitta, N. V., D. V. Reames, M. L. De Rosa, Y. Liu, S. Yashiro, and N. Gopalswamy  
599 (2006), Solar Sources of Impulsive Solar Energetic Particle Events and Their Magnetic  
600 Field Connection to the Earth, *Astrophys. J.*, , *650*, 438–450, doi:10.1086/507442.
- 601 Patsourakos, S., A. Vourlidis, Y. M. Wang, G. Stenborg, and A. Thernisien (2009), What  
602 Is the Nature of EUV Waves? First STEREO 3D Observations and Comparison with  
603 Theoretical Models, *Solar Phys.*, *259*, 49–71, doi:10.1007/s11207-009-9386-x.
- 604 Plunkett, S. P., B. J. Thompson, R. A. Howard, D. J. Michels, O. C. St. Cyr, S. J.  
605 Tappin, R. Schwenn, and P. L. Lamy (1998), LASCO observations of an Earth-directed  
606 coronal mass ejection on May 12, 1997, *Geophys. Res. Lett.*, *25*, 2477–2480, doi:10.1029/  
607 98GL50307.
- 608 Posner, A. (2007), Up to 1-hour forecasting of radiation hazards from solar energetic  
609 ion events with relativistic electrons, *Space Weather*, *5*(5), n/a–n/a, doi:10.1029/  
610 2006SW000268, s05001.
- 611 Qin, G., Y. Wang, M. Zhang, and S. Dalla (2013), Transport of Solar Energetic Particles  
612 Accelerated by ICME Shocks: Reproducing the Reservoir Phenomenon, *Astrophys. J.*,  
613 *766*, 74, doi:10.1088/0004-637X/766/2/74.
- 614 Reames, D. V. (1999), Particle acceleration at the Sun and in the heliosphere, *Space Sci.*  
615 *Rev.*, *90*, 413–491, doi:10.1023/A:1005105831781.

- 616 Thompson, B. J., S. P. Plunkett, J. B. Gurman, J. S. Newmark, O. C. St. Cyr, and D. J.  
617 Michels (1998), SOHO/EIT observations of an Earth-directed coronal mass ejection on  
618 May 12, 1997, *Geophys. Res. Lett.*, *25*, 2465–2468, doi:10.1029/98GL50429.
- 619 Thompson, B. J., B. Reynolds, H. Aurass, N. Gopalswamy, J. B. Gurman, H. S. Hudson,  
620 S. F. Martin, and O. C. St. Cyr (2000), Observations of the 24 September 1997 Coronal  
621 Flare Waves, *Solar Phys.*, *193*, 161–180, doi:10.1023/A:1005222123970.
- 622 Torsti, J., et al. (1995), Energetic Particle Experiment ERNE, *Solar Phys.*, *162*, 505–531,  
623 doi:10.1007/BF00733438.
- 624 Tylka, A. J., C. M. S. Cohen, W. F. Dietrich, S. Krucker, R. E. McGuire, R. A. Mewaldt,  
625 C. K. Ng, D. V. Reames, and G. H. Share (2003), Onsets and Release Times in Solar  
626 Particle Events, *International Cosmic Ray Conference*, *6*, 3305.
- 627 Vainio, R., et al. (2013), The first SEP Server event catalogue ~68-MeV solar proton events  
628 observed at 1 AU in 1996-2010, *Journal of Space Weather and Space Climate*, *3*(27),  
629 A12, doi:10.1051/swsc/2013030.
- 630 Veronig, A. M., M. Temmer, and B. Vršnak (2008), High-Cadence Observations of a Global  
631 Coronal Wave by STEREO EUVI, *Astrophys. J.*, *681*, L113–L116, doi:10.1086/590493.
- 632 von Rosenvinge, T. T., et al. (2008), The High Energy Telescope for STEREO, *Space Sci.*  
633 *Rev.*, *136*, 391–435, doi:10.1007/s11214-007-9300-5.
- 634 Wang, L., R. P. Lin, S. Krucker, and J. T. Gosling (2006), Evidence for double injections  
635 in scatter-free solar impulsive electron events, *Geophys. Res. Lett.*, *33*, L03106, doi:  
636 10.1029/2005GL024434.
- 637 Wiedenbeck, M. E., G. M. Mason, C. M. S. Cohen, N. V. Nitta, R. Gómez-Herrero,  
638 and D. K. Haggerty (2013), Observations of Solar Energetic Particles from  $^3\text{He}$ -rich

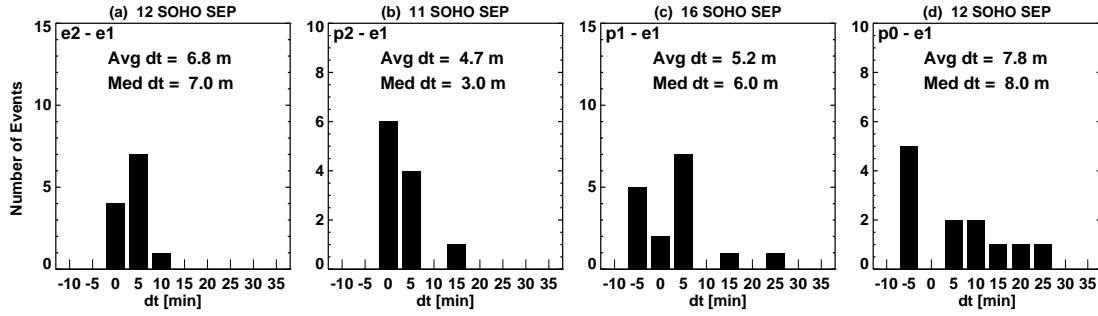


639 Events over a Wide Range of Heliographic Longitude, *Astrophys. J.*, , 762, 54, doi:  
640 10.1088/0004-637X/762/1/54.

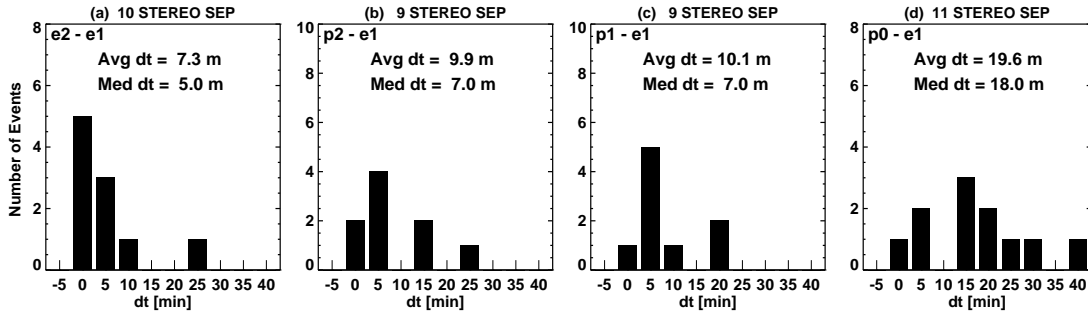
641 Wuelser, J.-P., et al. (2004), EUVI: the STEREO-SECCHI extreme ultraviolet imager,  
642 in *Telescopes and Instrumentation for Solar Astrophysics, Society of Photo-Optical In-*  
643 *strumentation Engineers (SPIE) Conference Series*, vol. 5171, edited by S. Fineschi and  
644 M. A. Gummin, pp. 111–122, doi:10.1117/12.506877.



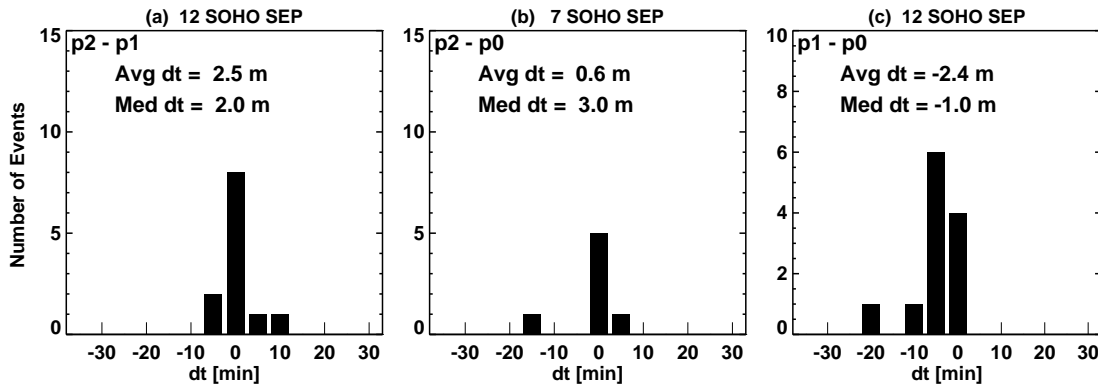
**Figure 1.** 1-minute averaged intensity of near-relativistic electrons (2.64–10.4 MeV) from SOHO/EPHIN observations for: a) the 2011 August 9 SEP and b) the 2011 August 4 SEP. Horizontal lines give the background level (solid), the average intensity during a pre-event time interval, and the background  $\pm 3\sigma$  levels (dashed–dotted). The inclined line is the linear fit to the logarithm of the SEP intensity during the early rise of the event. The onset time is the time of intersection of this line with the background, the gray rectangle indicates the uncertainty. The orange and blue dashed lines in (b) are two assumed background levels, illustrating how the elevated background levels affect SEP onset times.



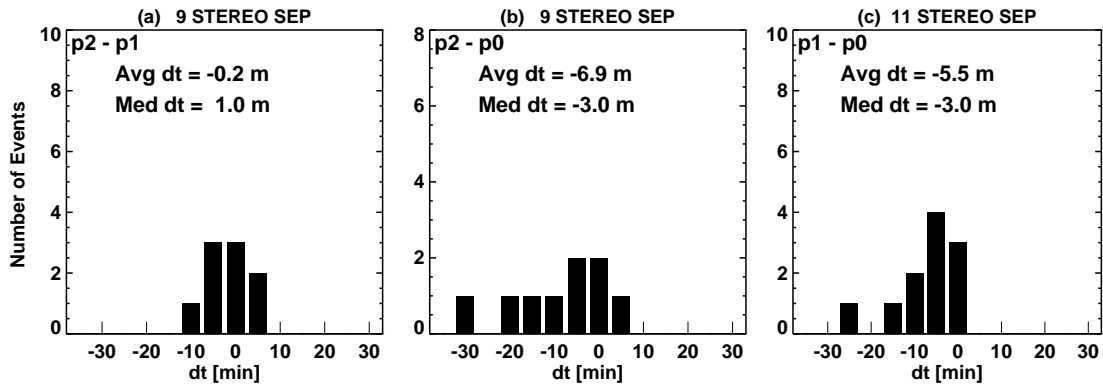
**Figure 2.** Histograms of time differences for 17 SOHO SEP events between: (a) e2 and e1 SPRs, (b) p2 and e1 SPRs, (c) p1 and e1 SPRs and (d) p0 and e1 SPRs.



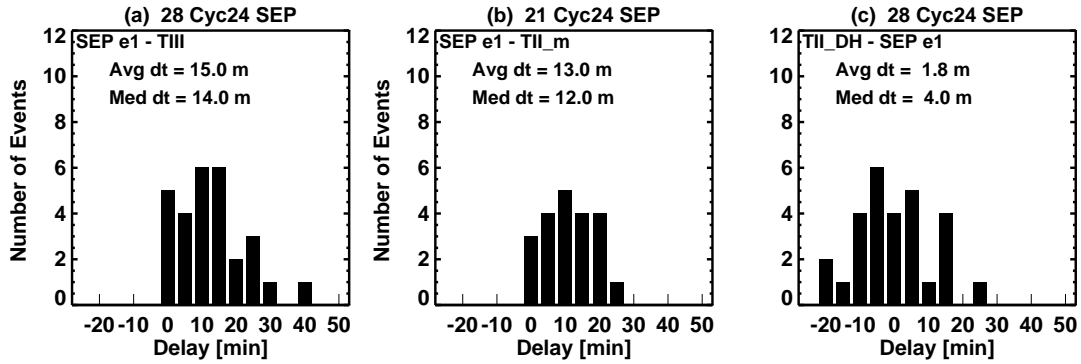
**Figure 3.** Histograms of time differences for the 11 STEREO SEP events between: (a) e2 and e1 SPRs, (b) p2 and e1 SPRs, (c) p1 and e1 SPRs and (d) p0 and e1 SPRs.



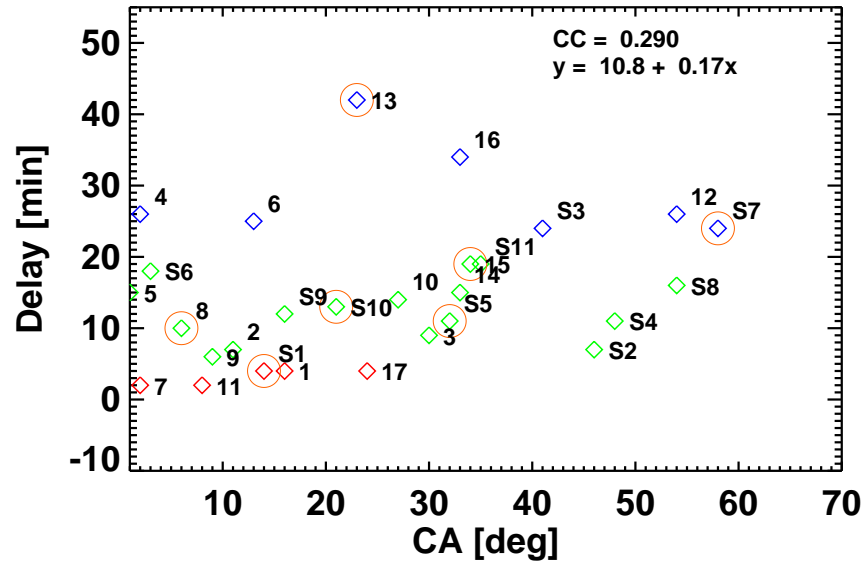
**Figure 4.** Histograms of time differences for SOHO SEP events between: (a) p2 and p1 SPRs, (b) p2 and p0 SPRs, and (c) p1 and p0 SPRs.



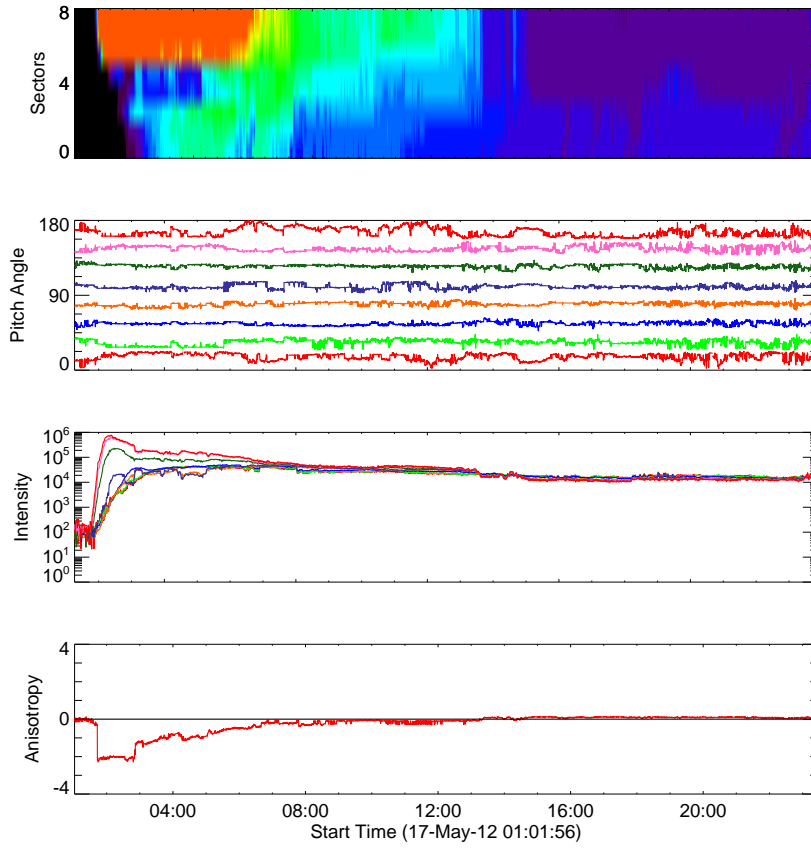
**Figure 5.** Histograms of time differences for STEREO SEP events between: (a) p2 and p1 SPRs, (b) p2 and p0 SPRs, and (c) p1 and p0 SPRs.



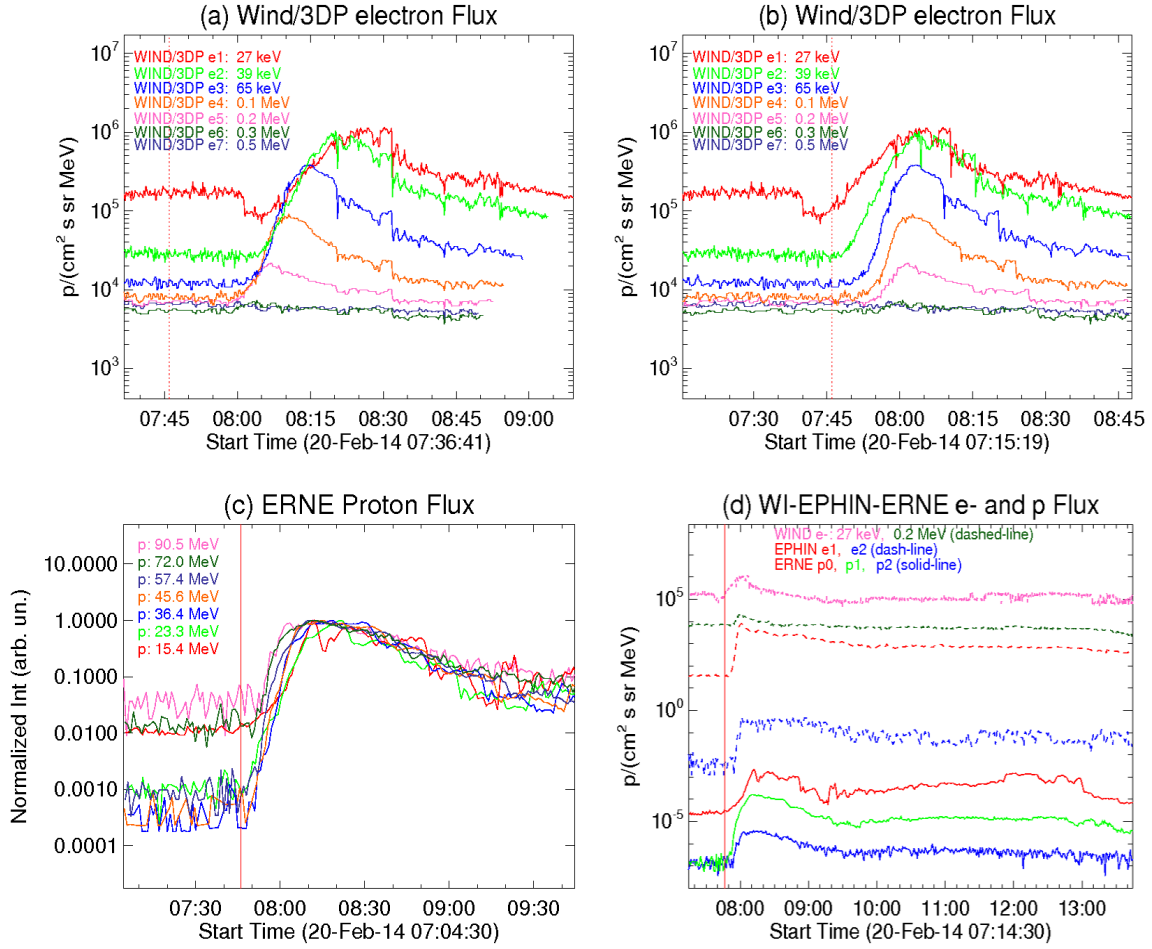
**Figure 6.** Time differences between (a) e1 SPR times and type III onset times, (b) e1 SPR times and metric type II onset times, and (c) e1 SPR times and DH type II onsets.



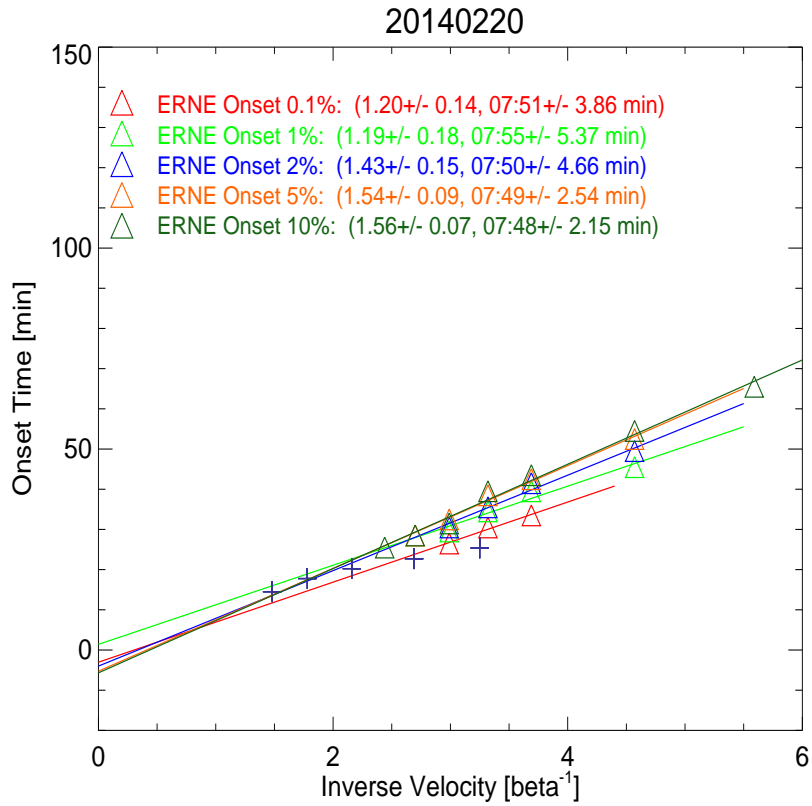
**Figure 7.** Delays between the e1 release times and type III onsets as a function of CAs. Red, green and blue colors mark three groups with delays  $dt \leq 5$  min,  $5 < dt < 20$  min, and  $dt \geq 20$  min. Circles denote the events lack of associated type II bursts



**Figure 8.** Anisotropy and intensity time profiles of the SEP event on May 17 2012 observed by Wind/3DP.

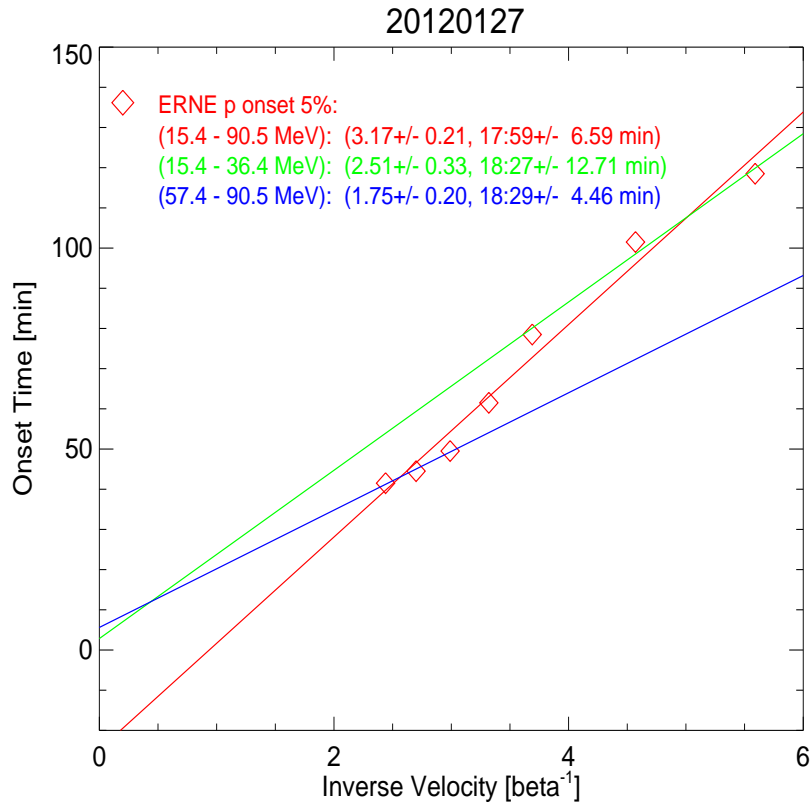


**Figure 9.** SEP intensity on 2014 February 20: (a) 0.027 – 0.5 MeV electron intensity from Wind/3DP, (b) time-shifted 0.027 – 0.5 MeV electron intensity from Wind/3DP, c) 15.4 – 90.5 MeV normalized and time-shifted intensity from ERNE and d) over-plotted electron and proton intensity from Wind/3DP, EPHIN, and ERNE.

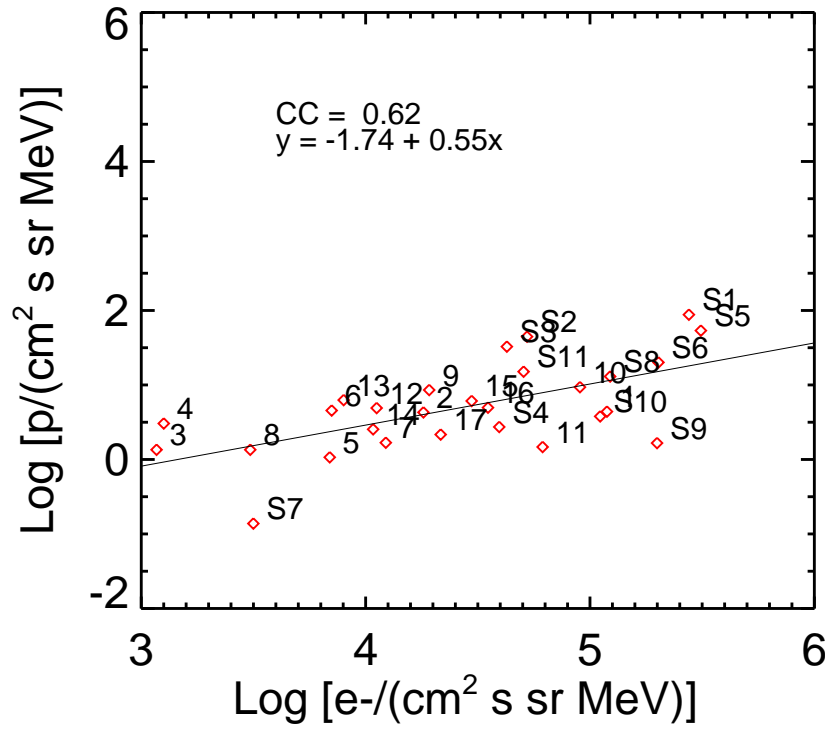


**Figure 10.** The VDA based on onset times at 0.1%, 1%, 2%, 5% and 10% of the peak value.

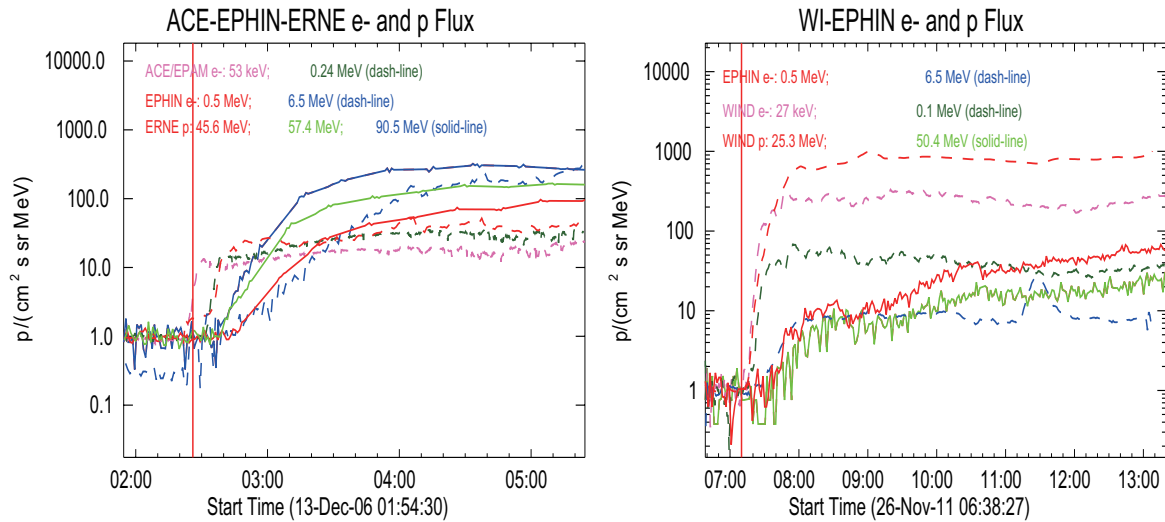




**Figure 11.** The VDA based on 57.4–90.5 MeV (blue), 15.4–57.4 MeV (green) and 15.4–90.5 MeV energy channels.



**Figure 12.** Logarithmic peak intensity correlation between the e1 electrons and the p0 protons.



**Figure 13.** (Left) over-plotted electron and proton intensity from ACE/EPAM, EPHIN, and ERNE on December 13 2006. (Right) over-plotted electron and proton intensity from WIND/3DP electrons, EPHIN, and WIND/EPACT protons on November 26 2011. The intensity has been normalized to the background flux level for easy comparison.

**Table 1.** SEP Electrons and Protons Solar Release Times and Associated Solar Eruptive Signatures

#	Date	EPHIN SPR		p1	ERNE SPR		p3	Type			Spd <i>km/s</i>	Loc	Ht Rs	SC	CA <sup>d</sup> °
		e1 UT	e2 UT		p2 UT	Type III UT		Type II mII UT	Type II DH UT						
1 <sup>a</sup>	2006/12/13	02:30 ± 3	02:39 <sup>+3</sup> <sub>-12</sub>	02:36 ± 5	02:36 ± 5	—:—	02:26	02:26	02:45	1774	S06W23	2.7	S	16	
2 <sup>c</sup>	2006/12/14	22:17 ± 3	22:24 ± 11	22:23 ± 5	22:24 ± 5	—:—	22:10	22:09	22:30	1042	S06W46	2.4	S	11	
3	2010/08/14	10:05 ± 3	—:—	—:—	10:12 ± 5	10:15 ± 5	09:56	09:52	10:00	1205	N17W52	2.9	S	30	
4	2011/03/07	20:18 ± 5	—:—	—:—	20:27 ± 5	20:30 ± 13	19:52	19:54	20:00	2125	N31W53	8.7	S	2	
5	2011/06/07	06:41 ± 12	06:45 ± 7	06:42 ± 8	06:40 ± 12	—:—	06:26	06:25	06:45	1255	S21W54	3.8	S	1	
6	2011/08/04	04:17 ± 3	04:31 ± 10	04:23 ± 5	04:18 ± 5	04:22 ± 14	03:52	03:54	04:15	1315	N19W36	6.0	S	13	
7 <sup>a</sup>	2011/08/09	08:04 ± 3	08:12 <sup>+3</sup> <sub>-12</sub>	08:01 ± 5	08:00 ± 5	07:59 ± 5	08:02	08:01	08:20	1610	N17W69	2.1	S	2	
8 <sup>b</sup>	2011/11/26	07:20 ± 3	07:29 ± 7	—:—	07:45 ± 10	07:46 ± 10	07:10	—:—	07:15	933	N17W49	3.5	S	6	
9	2012/01/27	18:22 ± 3	18:27 ± 3	18:30 ± 5	18:28 ± 5	18:45 ± 12	18:16	18:10	18:30	2508	N27W71	3.2	S	-9	
10	2012/03/13	17:31 ± 3	17:35 ± 3	17:32 ± 5	17:32 ± 5	17:29 ± 9	17:17	17:15	17:35	1884	N19W66	3.3	S	-27	
11	2012/05/17	01:34 ± 3	01:40 ± 3	01:37 ± 5	01:31 ± 5	01:33 ± 5	01:32	01:31	01:40	1582	N11W76	2.3	S	-8	
12 <sup>b</sup>	2012/07/12	16:51 ± 5	—:—	—:—	16:58 ± 10	16:59 ± 10	16:31	16:25	16:45	885	S15W01	2.9	S	54	
13	2012/07/17	14:43 ± 5	—:—	—:—	14:43 ± 10	14:51 ± 10	14:01	—:—	14:40	958	S28W75	4.4	S	-23	
14 <sup>c</sup>	2012/07/19	—:—	—:—	06:06 ± 15	05:53 ± 11	—:—	05:25	05:24	05:30	1631	S13W88	9.1	S	-33	
15	2013/05/22	13:29 ± 6	13:32 ± 3	13:30 ± 5	13:27 ± 5	13:26 ± 6	13:10	—:—	13:10	1466	N13W75	6.0	S	-34	
16 <sup>c</sup>	2014/01/07	18:38 ± 9	18:47 ± 5	18:43 ± 10	18:46 ± 14	—:—	18:04	18:17	18:27	1830	S19W29	8.6	S	33	
17	2014/02/20	07:50 ± 3	07:54 ± 3	07:51 ± 5	07:49 ± 5	07:46 ± 15	07:46	07:45	08:06	1040	S15W73	2.8	S	-24	
S1	2011/03/21	02:25 ± 5	02:31 ± 5	02:32 ± 5	02:31 ± 5	02:33 ± 5	02:21	—:—	02:30	1341	N26W41	2.6	A	14	
S2	2011/09/22	10:47 ± 5	10:55 ± 5	10:53 ± 5	10:54 ± 5	11:05 ± 5	10:40	10:39	11:05	1905	N09W07	2.7	B	46	
S3 <sup>c</sup>	2012/03/07	00:42 ± 9	00:44 ± 6	00:46 ± 5	00:51 ± 5	01:14 ± 22	00:18	00:17	00:36	2684	N22W105	7.0	B	-41	
S4	2012/05/26	20:57 ± 5	21:02 ± 6	21:04 ± 7	20:59 ± 6	21:02 ± 5	20:46	20:47	20:50	1966	N11W11	2.4	A	48	
S5 <sup>c</sup>	2012/07/23	02:25 ± 5	02:53 ± 16	02:50 ± 6	02:49 ± 5	02:48 ± 6	02:14	—:—	02:30	2003	N05W15	3.0	A	32	
S6	2012/08/31	20:03 ± 5	20:05 ± 5	20:18 ± 5	20:17 ± 5	20:21 ± 5	19:45	19:42	20:00	1442	S19W73	3.0	B	3	
S7 <sup>c</sup>	2013/03/15	07:03 ± 10	—:—	—:—	—:—	07:27 ± 18	06:39	—:—	07:00	980	N11W128	3.9	B	-58	
S8	2013/04/11	07:19 ± 5	07:21 ± 5	07:27 ± 5	07:24 ± 5	07:22 ± 5	07:03	07:02	07:10	861	N09W129	1.7	B	-54	
S9	2013/05/13	02:20 ± 5	02:24 ± 6	02:37 ± 9	02:41 ± 7	02:47 ± 10	02:08	02:10	02:20	1366	N12W77	2.2	B	-16	
S10	2013/06/21	03:04 ± 10	03:16 ± 12	—:—	—:—	03:45 ± 15	02:51	—:—	03:36	1900	S16W66	2.8	B	-21	
S11	2014/02/25	01:05 ± 5	01:09 ± 5	01:05 ± 5	01:12 ± 5	01:22 ± 5	00:46	00:56	01:02	2147	S12W78	3.7	B	-35	

<sup>a</sup> X-ray contamination electron event<sup>b</sup> Data from WIND/EPACT protons being used when SOHO's roll angle is 180°.<sup>c</sup> High background flux level event<sup>d</sup> With a large uncertainty of 20–30 °

**Table 2.** Electron Anisotropy and Velocity Dispersion Analysis Results for Protons

#	Date	Aniso A	Electron		Proton VDA		
			SPR_e1 (UT)	SPR_e2 (UT)	SPR_p (UT)	$L_{path}$ (AU)	energy (low-high) (MeV)
1	2006/12/13	1.07	02:30	02:39	02:31 $\pm$ 1.76	1.54 $\pm$ 0.08	57.4 90.5
2	2006/12/14	1.17	22:17	22:24	HBG	—	— —
3	2010/08/14	-0.90	10:05	—:—	10:13 $\pm$ 3.03	1.27 $\pm$ 0.09	15.4 57.4
4	2011/03/07	-1.42	20:18	—:—	20:17 $\pm$ 4.0	1.61 $\pm$ 0.10	— —
5	2011/06/07	-1.24	06:41	06:45	06:47 $\pm$ 4.0	1.35 $\pm$ 0.10	25.3 50.4
6	2011/08/04	-1.55	04:17	04:31	04:36 $\pm$ 6.35	1.19 $\pm$ 0.17	15.4 45.6
7	2011/08/09	1.41	08:04	08:12	08:03 $\pm$ 6.06	1.18 $\pm$ 0.24	57.4 72.0
8	2011/11/26	-2.09	07:20	07:29	07:35 $\pm$ 4.0	1.30 $\pm$ 0.10	25.3 50.4
9	2012/01/27	-0.27	18:22	18:27	18:27 $\pm$ 12.71	2.51 $\pm$ 0.33	15.4 57.4
10	2012/03/13	-1.96	17:31	17:35	17:34 $\pm$ 2.82	1.24 $\pm$ 0.09	15.4 90.5
11	2012/05/17	-2.23	01:34	01:40	IC	—	— —
12	2012/07/12	2.13	16:57	—:—	16:56 $\pm$ 4.0	1.30 $\pm$ 0.10	25.3 50.4
13	2012/07/17	-1.10	14:43	—:—	14:44 $\pm$ 0.66	1.19 $\pm$ 0.02	15.4 45.6
14	2012/07/19	-0.44	—:—	—:—	HBG	—	— —
15	2013/05/22	-1.07	13:29	13:32	13:30 $\pm$ 4.0	1.36 $\pm$ 0.10	0.0 50.4
16	2014/01/07	0.65	18:38	18:47	HBG	—	— —
17	2014/02/20	1.94	07:50	07:54	07:51 $\pm$ 3.86	1.20 $\pm$ 0.14	23.3 57.4
S1	2011/03/21	-1.37	02:25	02:31	02:29 $\pm$ 1.63	1.25 $\pm$ 0.04	11.0 50.0
S2	2011/09/22	2.24	10:47	10:55	10:47 $\pm$ 4.45	1.58 $\pm$ 0.10	11.0 38.0
S3	2012/03/07	-1.08	00:42	00:44	00:42 $\pm$ 9.79	1.78 $\pm$ 0.23	11.0 50.0
S4	2012/05/26	1.98	20:57	21:02	20:58 $\pm$ 3.74	1.42 $\pm$ 0.09	11.0 50.0
S5	2012/07/23	1.28	02:25	02:53	02:56 $\pm$ 1.34	1.26 $\pm$ 0.05	38.0 50.0
S6	2012/08/31	2.97	20:03	20:05	20:16 $\pm$ 0.86	1.56 $\pm$ 0.02	18.1 38.0
S7	2013/03/15	1.44	07:03	—:—	NA	—	— —
S8	2013/04/11	2.52	07:19	07:21	07:22 $\pm$ 0.68	1.50 $\pm$ 0.02	11.0 50.0
S9	2013/05/13	-0.92	02:20	02:24	02:33 $\pm$ 0.04	1.65 $\pm$ 0.00	11.0 50.0
S10	2013/06/21	1.76	03:04	03:16	03:34 $\pm$ 1.39	1.54 $\pm$ 0.03	11.0 25.1
S11	2014/02/25	NA	01:05	01:09	01:09 $\pm$ 1.87	1.40 $\pm$ 0.05	11.0 50.0

**Table 3.** Energy channels used in the SOHO/ERNE velocity dispersion analysis

	Channel	Energy range (MeV)	Average energy (MeV)	Inverse speed ( $\beta^{-1}$ )
LED	0	1.58-1.78	1.68	16.7
	1	1.78-2.16	1.97	15.5
	2	2.16-2.66	2.41	14.0
	3	2.66-3.29	2.98	12.6
	4	3.29-4.10	3.70	11.3
	5	4.10-5.12	4.71	10.0
	6	5.12-6.42	5.72	9.10
	7	6.42-8.06	7.15	8.15
	8	8.06-10.1	9.09	7.24
	9	10.1-12.7	11.4	6.47
HED	10	13.8-16.9	15.4	5.59
	11	16.9-22.4	18.9	5.06
	12	20.8-28.0	23.3	4.57
	13	25.9-32.2	29.1	4.11
	14	32.2-40.5	36.4	3.69
	15	40.5-53.5	45.6	3.32
	16	50.8-67.3	57.4	2.99
	17	63.8-80.2	72.0	2.70
	18	80.2-101	90.5	2.44
	19	101-131	108	2.26