ONSET STUDY OF IMPULSIVE SOLAR ENERGETIC PARTICLE EVENTS

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ABSTRACT

Impulsive solar energetic particle (SEP) events are associated with impulsive X-ray flares, energetic electrons, and enhanced heavy ion abundances. Using instruments on ACE, we have examined the composition and origin of twelve impulsive SEP events from November 1997 to June 2000. All selected impulsive SEP events have enhanced $^{3}He/^{4}He$ ratios compared with the solar wind values. The range of $^{3}He/^{4}He$ ratios varies from 0.01 to 7.8. By assuming scatter-free propagation at zero degree pitch-angle, we fitted the minimum particle path lengths (from 1.2 to 1.4 AU, as expected), and estimated the ion event release time back at the Sun to within better than 30 minutes in most cases. We found only four events in which the release times agree for both 38-50 keV electrons and <1 MeV/nucleon ions. Five of our events have significant differences (>40 minutes) between the electron and ion onset times, all with ions injected later. Three impulsive ion events have no association with any impulsive electron event. Seven events have associated solar electromagnetic signatures (Type III radio bursts and/or X-ray flares).

INTRODUCTION

Impulsive solar energetic particle (SEP) events have been divided into two major classifications: gradual and impulsive. While gradual SEP events have been attributed to shock acceleration driven by coronal mass ejections, it is generally believed that impulsive SEP events are accelerated directly by solar flares (see review by Reames, 1999). The term impulsive was taken from the associated soft X-ray emission duration, by contrast with the gradual SEP events which generally have long-duration soft X-ray emission. However, the most distinctive characteristic that sets impulsive SEP events apart from gradual SEP events is the particle composition and charge state. In certain impulsive SEP events, $^{3}He/^{4}He$ ratios are found to be ~0.1 to 10 at energies ~ 100 keV/nucleon which are orders of magnitude higher than the coronal 2.5×10^{-4} values (Mason *et al.,* 1989; Reames 1999; and Ho *et al.*, 2001). In addition, the average charge states of iron are also found to be high (~Fe^{17+}) when compared with gradual SEP events (~Fe^{13+}). The high iron charge state indicates that the plasma within impulsive SEP events originates from regions that have temperatures ~ 10^{7} K. Hence it is hypothesized that impulsive SEP are accelerated directly from flares.

The short duration and small fluence of impulsive low-energy SEP ion events has made it difficult to study their onset and transport except for a few high fluence events in the past (Mason *et al.,* 1989). However, new instruments on the Advanced Composition Explorer (ACE) spacecraft orbiting the L1 point ~200 R_E upstream enable us to examine these impulsive ion events in greater detail than before.

In this paper, we present results using instruments on ACE to examine the onset of ions and electrons in impulsive SEP events and compare them with solar electromagnetic emissions from November 1997 to June 2000. The onsets of ions with energies ~ 20 keV/nucleon to 10 MeV/nucleon at 1 AU in impulsive SEP events are used to extrapolate their solar release time using a simple zero degree pitch-angle transport approximation. The solar release time is then compared with the onset of 38-53 keV electron events, and also with both X-ray and metric solar Type III radio bursts.

OBSERVATIONS

Energetic electron data from the Electron, Proton, and Alpha Monitor (EPAM) and ion data from the Ultra Low Energy Isotope Spectrometer (ULEIS) on the ACE spacecraft are presented in this paper. Details on the EPAM and ULEIS instruments can be found in Gold *et al.* (1998) and Mason *et al.* (1998), respectively. ACE was launched in August 1997 and is currently in a halo orbit around the L1 libration point (~200 Re) upstream of the Earth.

Twelve impulsive SEP events were selected from November 1997 to June 2000 from the ion velocity plots like the one shown in the top panel of Figure 1. These events were selected based on their relatively strong particle intensity and isolated onset. There were many additional impulsive SEP events detected on ACE (Ho *et al.*, 2001), but our onset detection algorithm requires a relatively low intensity prior to the onset of the event (see section below). Hence only twelve impulsive SEP events were selected. After these events were selected we found all twelve impulsive SEP events had enhanced ^{3}He/^{4}He ratios relative to the corona values. The event-averaged ^{3}He/^{4}He ratios are listed in Table 1. The ^{3}He/^{4}He ratio varies over three orders of magnitudes for the twelve events.

The first panel in Figure 1 shows the ion energy as a function of the arrival times of individual ions for an impulsive SEP event during May 1, 2000. Higher speed ions arrive at ACE before those at lower speed, thus leading to a characteristic curved pattern when plotted in this format. The one-minute sector-averaged 38-315 keV electron intensity measured on EPAM is plotted in second panel of Figure 1 for the same time period. After an impulsive event is identified, a linear fitting routine is applied to locate the onset times at 1 AU (as defined in the next section). This onset time is shifted back to the Sun to estimate the release time. We can also estimate the particle path length during transit from the Sun to 1 AU from the slope of the linear fit, as explained below.

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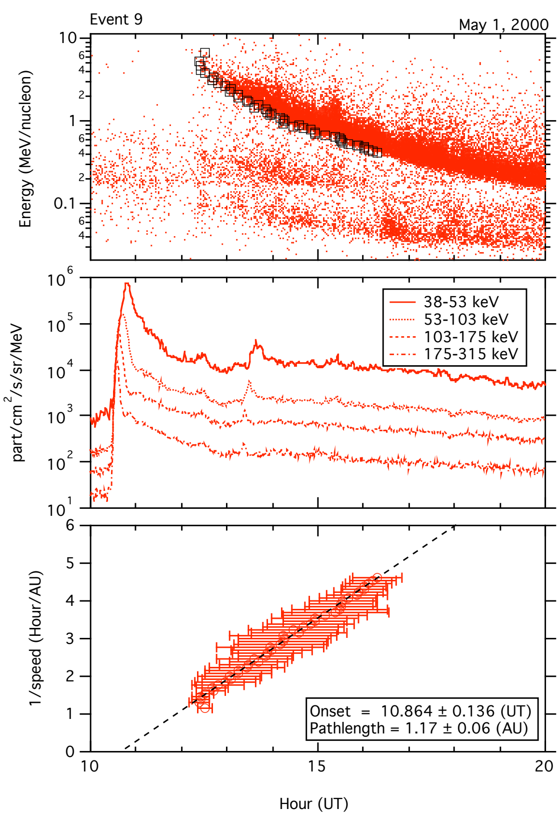

Fig. 1. The first panel shows the ULEIS Pulse-Height-Analyzed (PHA) data in velocity versus time format for an impulsive SEP event on May 1, 2000. The second panel shows the energetic electron data from EPAM for the same event. The third panel shows the fitted onset points identified by the edge detection algorithm.

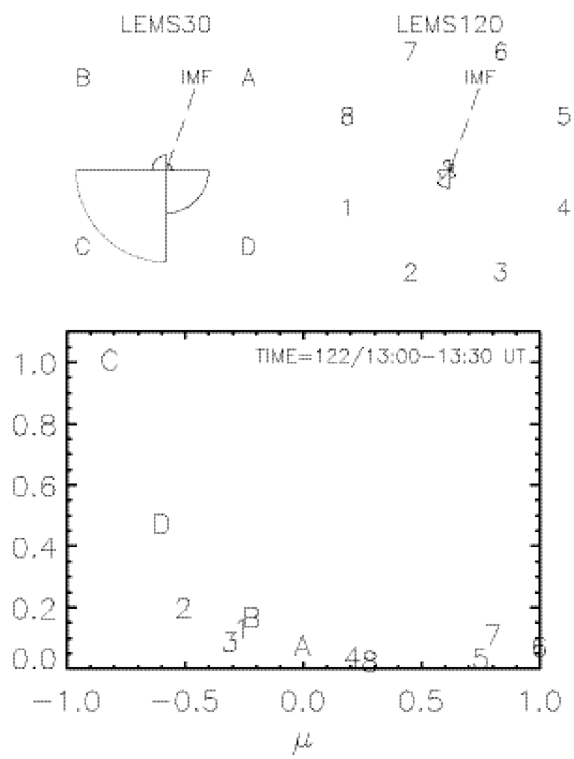

Fig. 2. Total 1.0-1.9 MeV ion pitch angle distribution measured by EPAM for the May 1, 2000 impulsive SEP event. The top two panels show the flux measured on two of the telescopes on EPAM (LEMS30 and LEMS1200 are 30° and 120° off the sunward pointing spin axis). Large anisotropies are seen in anti-sunward direction (along the IMF direction). The lower panel shows the pitch angle distribution in normalized intensity versus μ (pitch angle cosine).

Edge Detection

After an impulsive event is identified from the velocity versus time plot, the event is fitted with an edge detection routine to estimate the event onset at 1 AU for a range of energies. For every impulsive SEP event, we linearly bin the ion inverse velocity into either 50, 100 or 300 bins from 0.0 to 23 hour/AU according to the event intensity. This inverse velocity binning corresponds to logarithmically binning the particle velocity from infinity to 16.7 keV/nucleon. Since the energy range of ULEIS covers from 23 keV/nucleon to 14 MeV/nucleon, we only use those bins that correspond to energies from 180 keV/nucleon to 10 MeV/nucleon in order to locate the onset times for those most easily detected energetic ions. The routine then fits a half gaussian distribution to the PHA event for that inverse velocity bin for just the onset-to-maximum portion of the event, thus estimating the maximum and width of that distribution. At 1 AU, impulsive SEP events generally consist of very fast raise which is well described in first order by a half gaussian distribution. We define the two-sigma point prior to the maximum of the distribution as the onset for that inverse velocity bin. Hence, a set of onset points will be located as the routine scan for every inverse velocity bin (open squares in Figure 1).

Table 1. **The onset times of the twelve impulsive solar energetic particle events detected on ACE.**

Event	Date	Extrapolated Solar Released time for ~MeV Ions (UT)	Estimated Energetic Electron (38-53 keV) Released Time (UT) †	X-Ray Beg/max	RSP beg	Hα beg/max	$^3He/^4He$ (0.4 – 2.0 MeV/nuc)
1.	August 17, 1998	02:20 ± 00:23	01:41 – 01:51	…	02:26 CTM-1 02:55 III-1	…	0.11± 0.02
2.	August 18, 1998	04:23 ± 01:55	02:10 – 02:20	04:00/04:16 M1.5	04:18 III-2	04:13/04:13 N20W56 SF	8.0 ± 2.0
3.	April 5, 1999	04:34 ± 02:47	None	…	05:30 III-1	…	0.84 ± 0.09
4.	June 8, 1999	20:36 ± 02:06	None	…	19:43 III-1 21:19 III-1 21:55 III-1	…	2.0 ± 0.2
5.	July 3, 1999	17:21 ± 01:10	16:54	…	17:04 III-3	16:13/16:14 S15W43 SF	0.28 ± 0.02
6.	August 7, 1999	18:21 ± 00:38	17:03	18:52/19:25 M1.2	17:02 III-1, V-3 17:50 III-1	17:27/17:28 N18W40 SF 19:40/19:41 N17W41 SF	0.45 ± 0.09
7.	September 19, 1999	15:43 ± 00:21	14:19	14:07/14:40 C4.9	14:10 III-2, V-2, CTM-2	13:50/14:32 N24W64 B.9A	0.03 ± 0.02
8.	January 8, 2000	18:48 ± 00:45	None	…	…	…	0.59 ± 0.06
9.	May 1, 2000	10:52 ± 00:09	10:09	10:58/11:02 C1.0	10:57 III-1	11:00/11:02 S13W28 SF	0.08 ± 0.06
10.	June 4, 2000	08:43 ± 00:15	06:59	07:13/07:17 C1.5	07:02 III-2	…	0.22 ± 0.02
11.	June 15, 2000	21:06 ± 00:16	19:37	19:38/19:57 M1.8	19:37 III-1, V-2 19:43 II-1	19:40/19:45 N20W65 2N 20:56/21:04 N20W60 SF 21:02/21:02 N24W58 SF 21:06/21:11 N15W61 SF	0.04 ± 0.02
12.	June 28, 2000	22:09 ± 00:15	18:53‡	21:19/21:28 C9.9	…	21:19/21:28 N23W54 1F	0.01± 0.01

RSP = fixed-frequency radio burst; RBR = Sweep-frequency radio burst

† The estimated electron released time is calculated by subtracting the electron onset time at 1 AU by 20 minutes.

‡ The electron onset time determined from a prior large electron event.

Solar Release Time Extrapolation

Mason *et al.* (1989) have shown ~ 1 MeV/nucleon ions in impulsive SEP events exhibit nearly "scatter-free" propagation with large mean free path (λ > 0.5 AU). Figure 2 shows the 1.0-1.9 MeV ion angular sector distribution measured by the LEMS30 (top left) and LEMS120 (top right) telescopes of the EPAM instrument at the onset of the event on May 1, 2000. These distributions are 30 minute averages and normalized to the sector with maximum count rates (i.e., sector C in the LEMS30 telescope). The telescope looking towards the Sun (LEMS30) detects the bulk part of the distribution, whereas the telescope in the orthogonal direction (LEMS120) observes only very few energetic ions. Dashed lines labeled IMF in Figure 2 show the average interplanetary magnetic field direction projected into the rotation plane of each telescope. The magnetic field was steadily pointing towards the Sun throughout this event. The sectors with the highest count rates are opposite to the IMF direction; that means that the particles were mainly streaming along the magnetic field and in the anti-sunward direction. The bottom panel of Figure 2 shows the corresponding pitch-angle distribution transformed to the frame of reference co-moving with the solar wind and corrected for the Compton-Getting effect. The bulk of the ions has a pitch-angle cosine (μ) around -1 (FWHM μ<-0.65) which represents an extremely large anisotropy typically observed in impulsive particle events (Mason *et al.,* 1989).

If we assume the particles with different velocity travel along the same path from the Sun to 1 AU in impulsive events, we can fit a straight line to the onset times at 1 AU. The x-axis (1/v = 0) intercept of that straight line will be the extrapolated solar released time of the event and the slope of that line will depend on the particle pathlength as it travels from the Sun to 1 AU. The dashed line in the third panel in Figure 1 shows the fit to the onset times for the May 1, 2000 event.

Energetic Electron Comparison

Impulsive energetic electrons (>38 keV) are found to be associated with most (~60%) ^{3}He-rich impulsive SEP events (Ho *et al.,* 2001). After the onset time of an impulsive SEP event has been identified using ULEIS ion data, we search the EPAM data for the 38-53 keV energetic electron event that corresponds to the ion event. The second panel in Figure 1 shows the observed electron event at 1 AU associated with the impulsive event on May 1, 2000. Energetic electrons at 38-50 keV take approximately 20 minutes to travel 1.2 AU. So for comparison, the electron injection time at the Sun should be 20 minutes earlier than the onset time at 1 AU. This estimated time for the electron release may then be compared directly with the extrapolated solar release time for the ions. Table 1 lists the estimated solar release time for all twelve impulsive energetic ion events, and their respective closely associated energetic electron events. We only list those energetic electron events that are within 120 minutes of the impulsive ion event onsets (except Event 12 when a large electron event observed three hours prior to the ion event obscured our electron observation). For comparison, we also list the solar optical, radio and X-ray events that are presumably associated with both the ion and electron release at the Sun.

We found that nine of the twelve impulsive ^{3}He-rich SEP events had associated impulsive energetic electron events. In four of the nine (Events 1, 2, 5, and 9) related energetic electron events have estimated solar release times that are within the uncertainty of the extrapolated impulsive ion release time. The other six electron events have release times that are considerably earlier than the ion release times. Out of these five electron events, four (Event 7, 10, 11, 12) have relatively high electron intensity and long duration (~days). Hence we cannot rule out the possibility that there could be small impulsive electron injections during the decay phase of these four large electron events. However, the electron event that we identified as associated with Event 6 was of short duration and was injected more than 70 minutes prior to the ion release time.

Three of the impulsive ion events have no detectable energetic electron event at greater than 30 keV within 120 minutes of the impulsive ion event onsets despite low electron activity prior to and during the ion onsets. This proportion of events without detectable electrons is similar to the aforementioned larger survey by Ho *et al.* (2001) for the same energy.

Path-length Calculation

Reames and Stone (1986) have used the kilometric Type III emission associated with ^{3}He enhanced impulsive events to track the transport of the lower energy (<10 keV) electrons that generate the radio emission. They have found in some events that the trajectory of the Type III closely follows the nominal Parker spiral length with little scattering along the path. However, in some cases they could not determine the field lines connecting the source region with the observer since radio measurements only detect the centroid of the emission and cannot distinguish when there is more than one source of emissions.

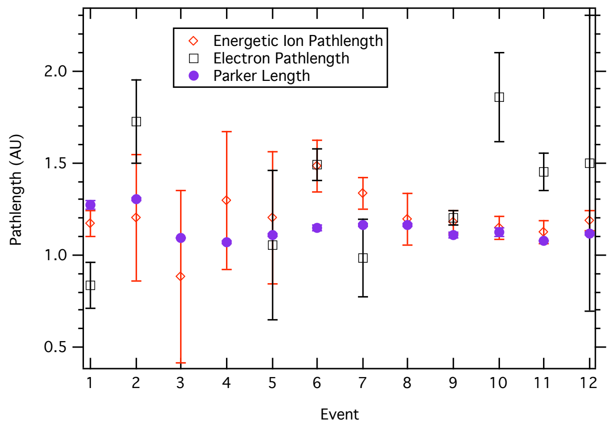

Fig. 3. Particle path-length for both electrons and ions from the Sun to 1 AU derived from fits to inverse velocity plots (red squares and open squares), along with the Parker spiral length obtained from the solar wind velocity (blue circles). Note that path-lengths for both electrons and ions generally agree well. However, the Parker spiral lengths are always smaller than those derived from energetic particles by about 10-15%. These could be simply explained by assuming a small scattering pitch angle (~30°) for particles as they transit from the Sun to 1 AU.

As mentioned in section 3.1, the slope of our linear fit to the onset times also gives the ion's path-length as it transits from the Sun to 1 AU. Figure 3 shows the estimated path-lengths of the twelve impulsive ^{3}He-rich ion events. Also shown in the figure is the predicted Parker spiral path-length calculated from the instantaneous solar wind speed measured from the ACE/SWEPAM instrument during the event onset. The electron detector on ACE/EPAM has four energy channels (38-53 keV; 53-103 keV; 103-175 keV; and 175-315 keV), so we can also determine the electron path-length from fitting the maximum of the four separate energy channels. As shown in Figure 3, the Parker spiral length estimated from the solar wind gives lower values (except Event 1, 2, 3 and 5) than those estimated from the ion onsets. The path-lengths derived from energetic ions and electrons are both consistent with each other and are about 10~15% (except for Event 10 and 11) higher than the Parker spiral length. This 10-15% difference is expected if we assume that particles travel along the magnetic field line with a finite cone angle instead of a zero degree pitch angle. The particle path is given as

$S = \frac{\Delta t}{V_{//}}$; $V_{//} = V \cdot \mu$; where V is the particle velocity, Δt is the transit time, and μ is the cosine of the pitch angle. Hence $S = \left(\frac{\Delta t}{V}\right)\left\langle \frac{1}{\mu} \right\rangle$, where $\left\langle \frac{1}{\mu} \right\rangle$ is the average of the inverse cosine along the trajectory. But since the pitch-angle distribution is confined to the anti-sunward hemisphere in these impulsive events, $\frac{1}{\mu} \approx 1 + \frac{\theta^2}{2}$, where θ is the pitch angle. The additional path length $\Delta S = S - S_0$ due to the finite pitch angle is therefore $\frac{\Delta S}{S_o} = \frac{S - S_o}{S_o} \approx \frac{\langle \theta^2 \rangle}{2}$. If we assume particles have an average pitch angle of 30º, then $\theta \approx 0.5$ or $\frac{\Delta S}{S_o} \approx 12.5\%$ which agrees with the difference between Parker spiral path-length and the estimated path lengths for both the ions and the electrons. We should note that the full-cone angle of the LEMS detectors is 51˚, hence we could not unambiguously identify pitch angles that are smaller than 45˚ even when the IMF is perfectly aligned with the center of the LEMS detectors.

DISCUSSION AND CONCLUSIONS

We have used a simple transport approximation to derive the solar release time of twelve energetic impulsive SEP events. All twelve impulsive SEP ion events that we studied are of short-duration (~ 10 hours), and ^{3}He/^{4}He rich. The onset times that we estimated from the simple transport approximation were compared with 38-53 keV electrons detected at 1 AU. In only four impulsive ion events did the estimated release times coincide within the uncertainties to those impulsive electron events. In the other five ion events, the accompanying impulsive electron events occurred from 70 to 180 minutes prior to the estimated solar release time of the impulsive ions. However, we could not rule out there could be small electron events released at a later time in four of the five events because the large electron flux from earlier injections could have obscured our observation. Furthermore, three additional ion events have no detectable electron event close to the estimated ion release time, despite quite low electron backgrounds prior to the ion events similar to the study by Ho *et al.* (2001). One possible explanation is that the onset time for energetic electrons is much easier to identify than low energy ions due to low background rate for electrons. We defined our ion onset time as the two-sigma point from the peak of the distribution, but in many of our electron events we could observe the electron onset many sigmas away from the peak distribution. Therefore, we may have an instrument related threshold delay in detecting the ion onset as compared to the electron onset. This effect would show up in all of the events we studied.

However, if we assume that we have correctly identified the associated electron events in nine of our twelve impulsive ion events, and we further assume the electrons and ions are accelerated by the same mechanism, it is then necessary to explain why the timing correlation between the ion release delayed after the electron release. In coronal mass ejection (CME) related gradual SEP events, Haggerty and Roelof (2002) have found a systematic delay in the energetic electron injection back at the Sun as compared to other solar electromagnetic signatures (for example Type III). Simnett *et al.* (2002) have invoked a CME driven shock to accelerate the observed electrons high (~2-3 solar radii) up in the corona that would explain the 12-13 minutes delay between their estimated solar injection time and the other solar electromagnetic signatures. If shocks are involved in accelerating both the near-relativistic electrons and the ions in these impulsive SEP events, then clearly the bulk of the ions are accelerated further from the Sun (i.e., later in the shock transit) than are the bulk of electrons. Another possibility in explaining the timing difference could be in these impulsive SEP events ions may have undergone further scattering than the electrons on the way from the Sun to 1 AU as postulated by Reames *et al.* (1985).

The transport approximation that we use also gives us an estimate of the particle transit path-length from their acceleration region to 1 AU. The estimated ion and electron path-lengths from the inverse velocity fitting often agree with each other and both are about 10-15% higher than that from the predicted Parker spiral lengths. This result can be explained simply by recognizing that the particles traveling along the magnetic field have a finite pitch angle distribution. In our case, a 30º mean pitch angle would account for the 12.5% difference between the path-length.

Krucker and Lin (2000) have studied ion and electron onsets and path-lengths in 26 gradual SEP events using the Wind/3DP instrument. They classified their events into two types according to the energetic proton path-length. In one type of event, the first arriving protons travel essentially scatter-free and have path-lengths between 1.1 and 1.3 AU. In the other type of event, the protons have traveled considerably longer path-lengths (~2 AU) during transit from the Sun to 1 AU. In all twelve impulsive SEP events that we studied here, we did not find any ion path-lengths that are longer than 1.5 AU. These could be due to statistics since we have a smaller event list than Krucker and Lin (2000).

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