Heavy Ion and Electron Release Times in Solar Particle Events

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Abstract

Using data from the SIS and EPAM instruments on ACE we have measured the onset times of 6 - 88 MeV/nuc ions and 38 - 315 keV electrons in 11 solar energetic particle (SEP) events from 1997 through 2002. We find that heavy ions are generally released later than electrons, by as much as ∼50 minutes. There is an apparent correlation between the release times (and the inferred release distances) and the ^{3}He/^{4}He ratio.

1. Introduction

The onset times of SEP events at 1 AU can be used to infer when particles are released into interplanetary space near the Sun, and, assuming acceleration by a CME-driven shock, to infer the distance from the Sun where particle release occurs. Haggerty and Roelof [5] studied the onsets of 79 beam-like near-relativistic electron events with ACE/EPAM. By tracing the electron onsets back to the Sun it was found that the electrons are typically released ∼10 minutes after soft x-ray, optical flare, and associated radio emission (see also [8]). In addition, the electron injections are well associated with western-hemisphere CMEs. Comparison with SOHO CME images shows that electrons are released when the west-limb CMEs are at ∼1 to ∼4 solar radii (R_s) [12].

This approach can also be used to investigate the acceleration and release of SEP ions [6,7]. From the EPAM list of beam-like electron events we identified events with sufficient intensity of Z ≥ 6 ions to measure onsets in the 6 to 88 MeV/nuc energy range with ACE/SIS. Eleven events satisfied the conditions of exhibiting velocity dispersion and having the magnetic field line (measured by ACE/MAG) within the SIS field of view. Particle velocity (v) was determined for Z ≥ 6 ions from the measured mass and energy of each ion. Heavy-ion onsets were identified in up to 8 velocity intervals by determining when the 2-minute or

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5-minute-average intensities first increased by $\sim 2.5\sigma$.

2. Observations

Figure 1 shows results for 3 of the 11 events. Also plotted are the onsets of 175 to 315 keV electrons [5], extrapolated onsets of CMEs based on SOHO data [12], and onsets of associated x-ray flares from GOES. The least-squares fits determine the pathlength (in AU) and the time when heavy ions were released near the Sun. Haggerty and Roelof [5] determined the electron onsets assuming a 1.2 AU pathlength and $0.73c$ average velocity. Note that in two of three cases the heavy ions were apparently released well after the electrons, while in the May 1 event the heavy-ion and electron timing is consistent. Krucker and Lin [7] also found 0.03 - 6 MeV ions to be released later than electrons in some events.

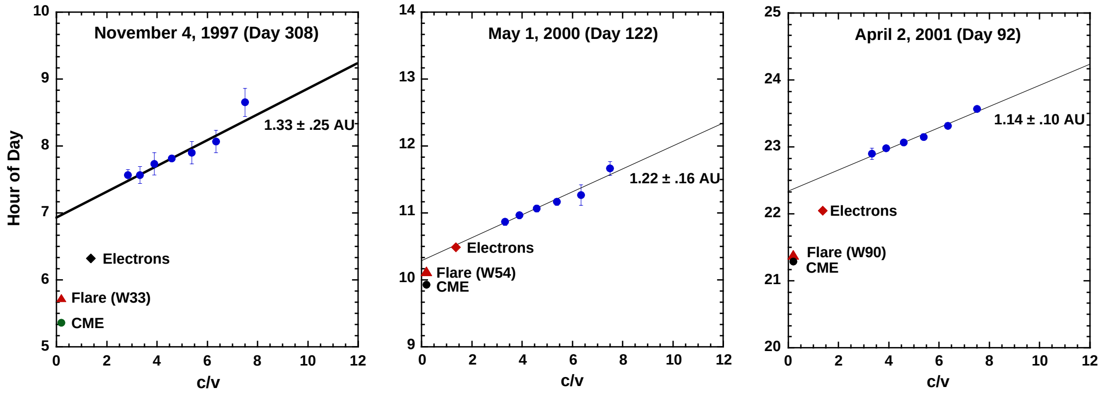

Fig. 1. Onset plots for SEP events plotted vs. c/v, where c is the speed of light. Extrapolating the fit to c/v = 0 gives the particle release time near the Sun. Also shown are CME launch times [12] and soft x-ray flare onsets.

Figure 2 shows histograms of electron and heavy-ion release times with respect to CME lift-off for the 9 events with available CME data. Note that the electrons are, on average, released sooner than the heavy ions, and that there is a greater spread in the heavy ion distribution. Comparison with CME data does not imply that these are all gradual events accelerated by CME-driven shocks; indeed, at least three of these events are thought to be flare-associated impulsive events [13,14,15]. To investigate the classification of these events further, Figure 3 shows the relative heavy-ion and electron timing and inferred heavy-ion release distance vs. the 5-13 MeV/nuc ^{3}He/^{4}He ratios. This approach appears to divide the events into two groups: (a) those with ^{3}He/^{4}He ratio >0.02 have similar ion and electron release times, and appear to be released within $<2\ R_s$ of the solar surface, while (b) those with ^{3}He/^{4}He <0.02 have greater ion-electron timing differences and appear to be released ~ 2 to $\sim 10\ R_s$ from the Sun.

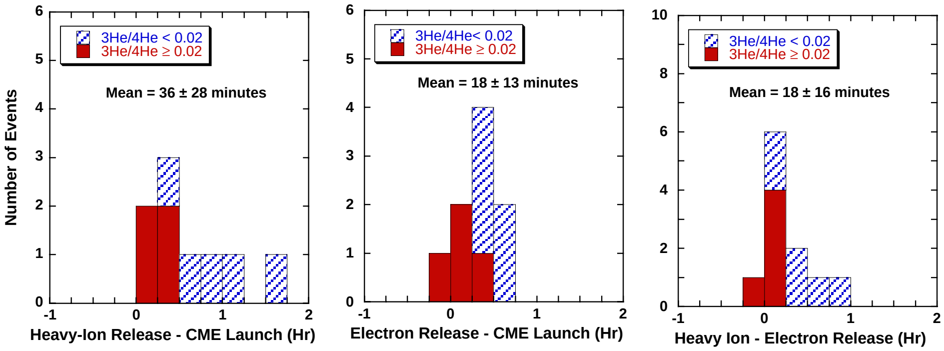

Fig. 2. Histograms of differences between the CME launch times and the inferred electron and heavy-ion release times. Events with enriched ^{3}He are indicated.

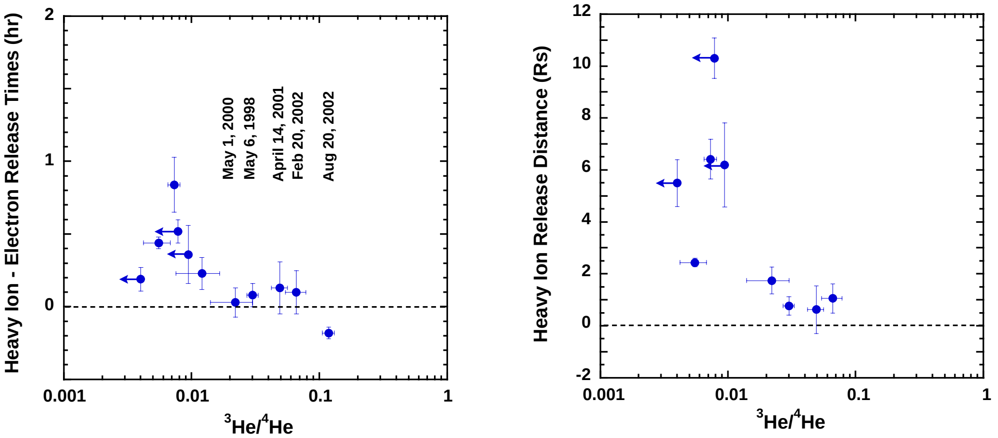

Fig. 3. (left): Correlation of the heavy-ion - electron release times with the ^{3}He/^{4}He ratio. (right): Correlation of the heavy-ion release distances with ^{3}He/^{4}He.

3. Discussion

The significant differences between electron and heavy-ion release times found for some of these events are somewhat surprising if both species are shock accelerated (e.g., [14]). Possibilities that may warrant further investigation include: (a) Scattering: By selecting beam-like electron events it is assumed that scattering is minimized and that the first arriving particles have had small pitch angles all the way from the Sun. Perhaps the ions sometimes scatter more than electrons and have larger average pitch angles. The ion pathlength fits varied from ∼0.8 to ∼1.6 AU with a median of 1.2 AU. (b) Different injection times/locations: Perhaps electrons are injected/accelerated closer to the Sun than heavy ions (e.g., [2]). For example, maybe the shock must first encounter a remnant suprathermal seed population [9], or an earlier CME [4]. (c) Wave particle effects: Perhaps heavy ions are trapped behind the shock (e.g., [11]) and electrons are released sooner.

The correlations with ^{3}He/^{4}He (Figures 2 and 3) suggest that our sample includes both gradual and impulsive events, although a fast CME was associated with at least 10 of these events (August 20, 2002 is uncertain). There has been debate as to whether the May 6, 1998 event was impulsive or gradual [3,11,16]. Timing studies involving additional species over a broader energy range show that particle release coincided with the peak soft x-ray intensity, but are also consistent with CME-driven shock acceleration [14]. On the basis of the atypically large ^{3}He/^{4}He ratio, the impulsive-like composition [3], and the association with three known impulsive events [13,14,15] in Figure 3, we favor an impulsive origin for the May 6 ground-level event, as well as for the smaller February 20, event.

Among the suggested explanations for ^{3}He and Fe enrichments in gradual events are the shock-acceleration of remnant interplanetary ions from previous impulsive events [9], or the presence of flare-accelerated ions in large, well-connected Fe-rich events [1]. The timing results for the May 6 and February 20 events favor the latter explanation [1], but there are also three large Fe-rich events with ^{3}He/^{4}He < 0.2, and delays of 20 to 40 minutes that appear inconsistent with a direct flare origin [1] and favor the remnant hypothesis [9]. It is also possible that flare particles from the same event are further accelerated by the shock [10].

Timing and composition studies of additional events, as well as theoretical modeling, may help resolve the issues raised above.

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