Onsets and Release Times in Solar Particle Events

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Abstract

The time at which solar energetic particles (SEPs) are first released into interplanetary space, and its relation to CMEs and various photon emissions, are important clues to the site and nature of the SEP acceleration mechanism [1-5,7,8,10,11]. We examine velocity dispersion among onsets in electrons and ions from *Wind*, *ACE*, and *IMP8*, as well as available neutron monitors, to determine the solar release time. We present results for two large impulsive events (1 May 2000 and 14 April 2001) and three western ground level events (GLEs; 6 November 1997, 6 May 1998, and 15 April 2001). In the impulsive events, the particle release coincides with hard x-ray emission. But the large GLEs show delayed release with respect to γ-ray emission, consistent with acceleration by the CME-driven shock.

1. Data and Analysis

Figure 1 shows 5-minute-averaged *Wind*/LEMT ∼2-10 MeV/nuc ^{4}He as samples of the data we have used. Onsets were identified by requiring a $\geq 2\sigma$ increase, as defined by the mean and standard deviation preceding the event. The same technique was employed to identify onsets in neutron monitors and *IMP8*/Chicago >2 MeV electrons, except that higher time resolution (ranging from ∼2.6 s to 1 min) was used whenever statistics permitted. Onsets in *IMP8*/GSFC ∼80 MeV protons and *Wind*/3DP ∼100-400 keV electrons [5] were analyzed independently. *ACE*/SIS records the arrival time of individual ions at ∼10-160 MeV/nuc, with very low background (typically Galactic cosmic rays). We used the first-arriving $Z > 2$ ion in each 0.25-wide β^{-1}-bin (where β is the particle speed in units of light-speed) as the *ACE*/SIS onsets. In our analysis, we used the earliest observed neutron monitor onset, assigned at β^{-1} corresponding to the highest cutoff among the stations at which the event was observed.

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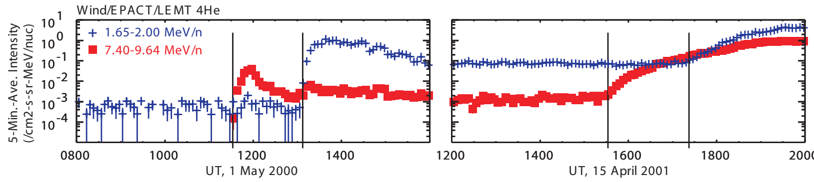

Fig. 1. Onsets in Wind/LEMT ^{4}He for the 1 May 2000 impulsive (left) and the 15 April 2001 ground level event (right). Vertical lines mark onset times.

Figure 2 shows linear fits to onset time vs. β^{-1} [5,7,10]. The intercept at $\beta^{-1} = 0$ is time of release into interplanetary space, and the slope gives the pathlength traveled by the first-arriving particles. The fitted pathlengths range from 1.1 to 1.7 AU, and release times have uncertainties <1 minute. The small number of *ACE*/SIS datapoints in the 15 April 2001 GLE is due to reduced livetime when count rates are high. No SIS data are shown for the 6 Nov. 1997 GLE. The magnetic field vector was outside the SIS field of view at the start of this event, and SIS observed its first ions >20 minutes after the fitted onset line.

2. Results and Discussion

Figure 3 compares the solar particle release time ("SPR", with dashed lines marking its uncertainty) with time profiles of *GOES* soft x-rays and hard x-rays or 4-7 MeV γ-rays (if observed) from *Yohkoh* or *Ulysses*. Onsets of metric (from *Solar Geophysical Data*) and DH (from *Wind*/Waves) type II and III radio emissions are marked, as well as the earliest *SOHO*/LASCO CME observations.

The two impulsive events have only one large hard x-ray peak, lasting ~1 minute. SPR coincides with this peak, consistent with the topology for flare-accelerated SEPs suggested by [9]: a rising loop reconnects with an overlying open flux line of opposite polarity, energizing particles and simultaneously sending them down into the solar atmosphere and up into interplanetary space.

In the GLEs, electrons >100 keV and ions from at least ~ 2 MeV/nuc to ~2 GeV/nuc are consistent with simultaneous departure from the Sun, indicating a common acceleration site. This has not always been reported in earlier studies [1,11], perhaps due to less sensitive instruments. However, in the 6 November 1997 and 15 April 2001 GLEs, SPR follows γ-ray emission by >5 minutes. (The Milagrito air shower array, which responds to >5 GeV protons, infers a release time for the 6 November 1997 GLE that is 8 ± 6 minutes earlier than ours, based on their data alone [2]. But even that release time falls well after the γ-rays.) SPRs are also significantly delayed with respect to onset of metric radio emission.

Some contrivance would be necessary to reconcile the delays in these two GLEs with acceleration at the flare. However, the timing is consistent with shock

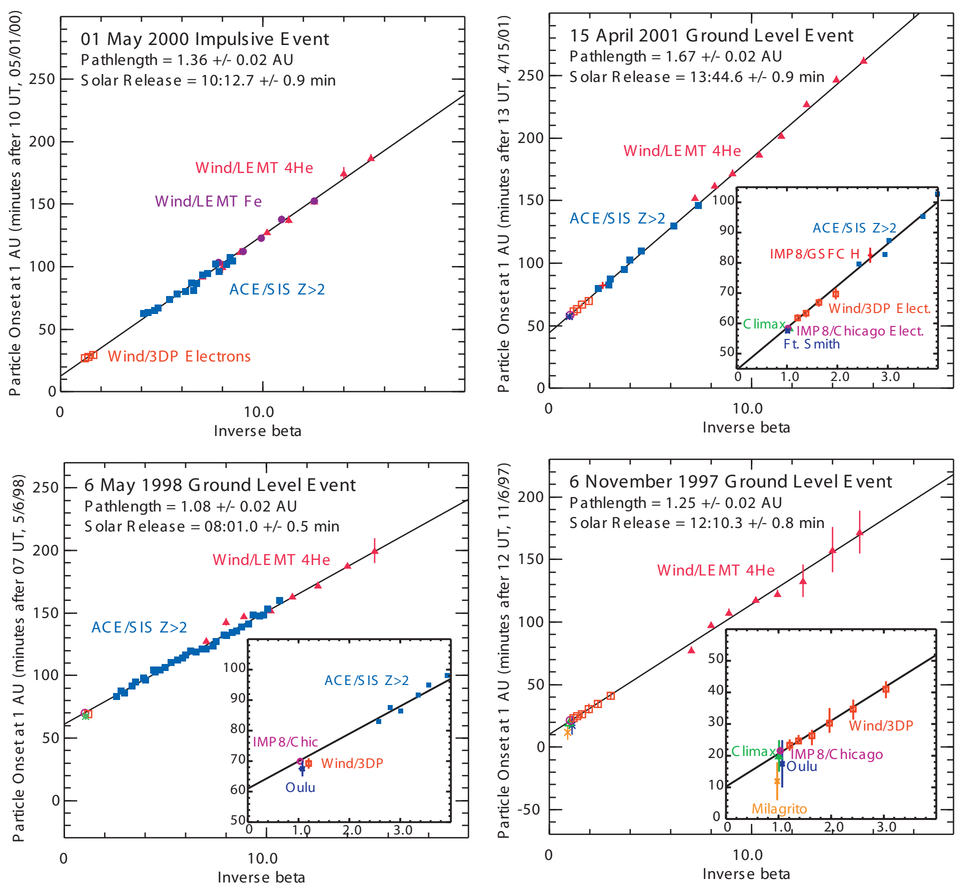

Fig. 2. Onset time vs. β^{-1} for four events. Insets show the region $\beta^{-1} \leq 4$.

acceleration and the magnetic topology described by [9]: as the CME launches, shearing in the underlying magnetic arcade causes reconnection, which sends energetic particles along closed loops into the solar atmosphere to generate hard x-rays, γ-rays, and neutrons. But production of the interplanetary particles we observe (except possibly for <100 keV electrons that generate type III radio emission) starts later, when the shock has formed and intercepted the Sun-Earth field line. Moreover, as 15 April 2001 illustrates, the shock can form quickly, producing multi-GeV ions before the CME reaches $\sim$2 R_s above the solar surface.

Above $\sim$30 MeV/nuc, 6 Nov. 1997 and 15 April 2001 have Fe/O approaching unity and Fe with mean charge $\sim$20 [6], both of which are characteristic of flare-accelerated ions. However, since Figure 3 argues against a *direct* flare origin, these results suggest re-acceleration of particles from preceding flare(s).

The bottom panel of Figure 3 shows the 6 May 1998 GLE. Of 10 GLEs in Cycle 23, this event ranks last in terms of proton fluence above 100 MeV. In this

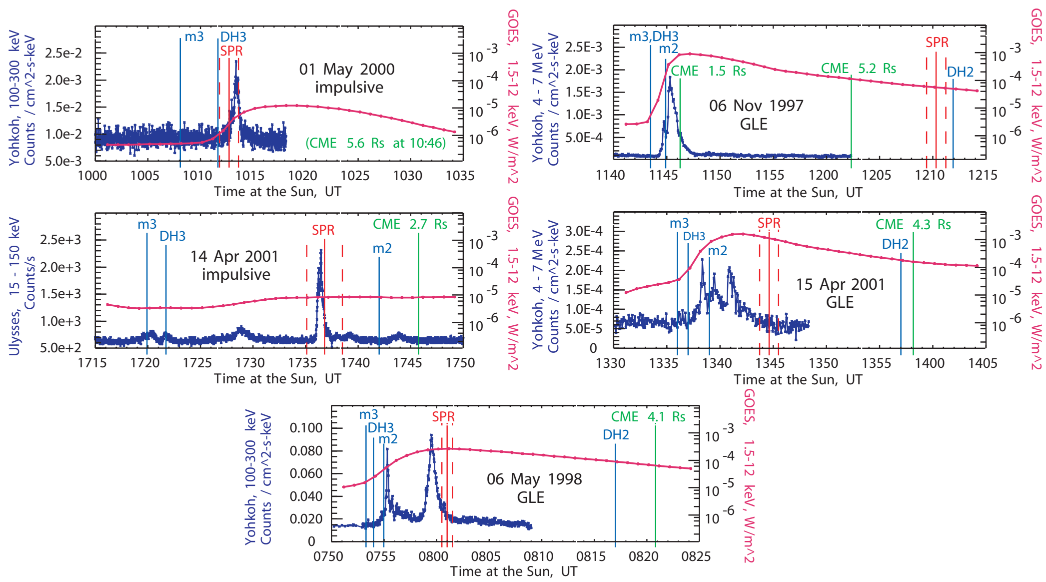

Fig. 3. Solar particle release ("SPR") times, radio onsets, and CME observations, compared to hard x- or γ-ray time profiles (left axis) and soft x-rays (right axis). Times have been corrected for travel from the Sun.

event, SPR nearly coincides with a peak in hard x-rays. However, SPR is also bracketed by onsets in metric and DH-type II emission, indicating that a shock was moving through the corona at the time of particle release. (This is not true for the impulsive events.) Thus, timing cannot distinguish between shock and flare origin in this particular event.

We thank K. Hurley, C. Lopate, R. Pyle, I. Usoskin, and E. Vashenyuk for data. AJT supported by NASA DPR S-13791G and the Office of Naval Research.

3. References

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