CORONAL MASS EJECTIONS AND THE INJECTION PROFILES
OF SOLAR ENERGETIC PARTICLE EVENTS

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Abstract
Previous studies using Skylab and Solwind coronagraph observations have shown that almost all E > 10 MeV solar energetic proton (SEP) events are associated with the occurrence of a coronal mass ejection (CME). These earlier studies did not address the relationship between the position of the associated CME and the timing of the injection of particles into the interplanetary medium. We have selected 10 cases in which a SEP event observed with the GSFC detectors on the IMP 8 or ISEE 3 spacecraft was correlated to a CME well observed by the Solwind coronagraph. We compare the height of the leading edge of the CME with the particle injection profiles for several energy ranges using the "solar release time" for the particles. The derived injection profiles are found to be increasing and sometimes reaching maximum while the associated CMEs are at heights of 2-10 Ro.

Introduction
The conditions under which SEPs are accelerated and injected into the interplanetary medium are poorly understood. Previous studies of the 1973-74 Skylab era (Kahler et al., 1978), the last solar maximum (Kahler et al., 1984a), and the 1983-85 approach to solar minimum (Kahler et al., 1987) have shown that nearly all E > 10 MeV SEP events observed at 1 AU are associated with large (> 40 degree widths), bright, fast (> 400 km/s) CMEs. The peak proton fluxes correlate roughly with the CME speeds. Not all fast CMEs are associated with observed SEP events, but the faster a given CME, the more likely is a SEP event association.

Two general ideas have been advanced to explain the CME association with SEP events. The first is that CMEs produce fast shocks which accelerate SEPs in the magnetically open corona over a region at least comparable to the size of the CME itself. The second is that the CMEs open previously closed magnetic fields from which trapped SEPs can escape to the interplanetary medium. In either case, the large angular sizes of the CMEs explain the region of fast propagation (Reinhard and Wibberenz, 1974) from which SEPs have rapid access to interplanetary space.

The goal of the previous studies was to determine the associations and statistical relationships between CMEs and SEP events. In no cases were detailed examinations of individual CME/SEP events undertaken. This leaves unclear the spatial positions of the CMEs during the times of SEP injections into the interplanetary medium. From the above discussion, it is apparent that the CMEs should have reached coronal heights dominated by open field lines (R > 2 Ro) during the SEP injections. This expectation is examined in a number of detailed cases in the present study.

Analysis
We began with a list of all associated Solwind CMEs and SEP events established in previous studies (Kahler et al., 1984a, 1987). We further required (1) that an Hα flare at longitude > W40 also be associated with the CME and (2) that the CME be well observed. The first requirement ensures that the SEP source is magnetically well connected to the Earth.
and that the CME is sufficiently close to the limb that the speed and position of its leading edge projected in the plane of the sky are close to the intrinsic values. The second requirement is simply that at least several images of the CME be available for height determinations. We selected 10 well observed events which are listed in Table 1.

<table>
<thead>
<tr>
<th>Date and Time of SEP Onset</th>
<th>Ha Flare</th>
<th>CME Onset and Speed</th>
</tr>
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<tr>
<td>1979 Aug 21 0700 UT</td>
<td>N17 W40 2B</td>
<td>0630 UT 875 km/s</td>
</tr>
<tr>
<td>1980 Nov 11 1830 UT</td>
<td>S11 W69 2B</td>
<td>1738 UT 1310</td>
</tr>
<tr>
<td>1981 Mar 7 0700 UT</td>
<td>S22 W79 -N</td>
<td>0634 UT 1400</td>
</tr>
<tr>
<td>1981 Apr 25 2130 UT</td>
<td>N09 W87 2B</td>
<td>2058 UT 970</td>
</tr>
<tr>
<td>1981 Apr 30 0330 UT</td>
<td>S43 W52 3B</td>
<td>0130 UT 1110</td>
</tr>
<tr>
<td>1981 Dec 5 1430 UT</td>
<td>N W42 E.F.1</td>
<td>1332 UT 800</td>
</tr>
<tr>
<td>1982 Feb 8 1330 UT</td>
<td>S14 W88 1B</td>
<td>1252 UT 1460</td>
</tr>
<tr>
<td>1982 Mar 7 0400 UT</td>
<td>N19 W53 2B</td>
<td>0320 UT 1490</td>
</tr>
<tr>
<td>1982 Nov 21 0700 UT</td>
<td>S12 W81 1N</td>
<td>0611 UT 885</td>
</tr>
<tr>
<td>1984 Feb 16 0930 UT</td>
<td>W130</td>
<td>0844 UT 1260</td>
</tr>
</tbody>
</table>

(1) Erupting prominence event described in Kahler et al. (1986).
(2) Event described in Debrunner et al. (1988).

From the GSFC energetic particle experiments on the IMP 8 and ISEE 3 spacecraft we derived flux profiles of 1 MeV electrons (ISEE 3 only), and of 5, 50, and 175 MeV protons. To compare the height of the leading edge of the observed CME with the times of the release of SEPs into interplanetary space, we assume the SEPs travel 1.3 AU along the spiral field lines at speed v with no scattering. We subtract times

\[ dt = 1.3 \text{ AU}/v - 8.3 \text{ min} \]  

(1)

from the observed times at 1 AU to derive the solar injection times matching the CME observations. This allows us to plot the injected particle fluxes as a function of the height of the associated CME. The plots for the 1 MeV electrons and 175 MeV protons are shown in Figures 1 and 2. The fluxes are corrected for background in all cases. In a few cases the background levels were too high to derive the SEP fluxes. In general the flux profiles are increasing or reaching maximum while the CMEs are moving through the field of view (2.5-10 Ro) of the Solwind coronagraph. We see little evidence for SEP injections before CMEs reach at least 2 Ro, at which point the coronal fields are predominately open.

There are two extreme possibilities for particle propagation to 1 AU. The first possibility is that the scattering mean free paths are large (> 1 AU), in which case the use of the "solar release time" (Neustock et al., 1985) is valid. To look for such events we have examined the flux anisotropies of several of the ISEE 3 events. In at least two events the fluxes are very anisotropic (A1/A0 > 1.0) for the early rise phase (0-3 hr). This is particularly true for the 1984 February 16 event (Debrunner et al., 1988). The other possibility for scattering is that the scattering mean free paths are short (< 0.1 AU). In this case the widths of the derived SEP injection profiles are on the order of 1-2 hr (e.g., Ma Sung and Earl, 1978). During a 2-hr interval the fastest CMEs can reach 10 Ro. We show in Figure 3 the heights of the leading edges of the 10 CMEs after the onsets of the associated type II bursts. Again we see that the likely injection times are characterized by leading edge locations high in the corona above the closed field regions.
Figure 1. Profiles of injected 1 MeV electron fluxes corrected by equation (1) versus the heights of the leading edges of the associated CMEs. Ha flare locations are given for each SEP event.

Figure 2. Same as Figure 1, but for 175 MeV protons.

Figure 3. Heights of the leading edges of the 10 CMEs of Table 1 as a function of time after the onset of the associated type II bursts. For the 6th and 9th events, which had no type II bursts, the time of peak of the microwave burst was used.

Discussion. We have compared the SEP injection profiles with the associated CME heights for 10 well observed cases. We find that the leading edges of the CMEs had attained heights of 2-10 Ro during the injection process. Thus the injection of SEPs in these events occurred in the context of rapid, large-scale changes in coronal structure produced by the CMEs. These
CMEs probably drove fast coronal shocks which produced type II bursts (Kahler et al., 1984b) and accelerated the SEPs. In contrast to the classic picture of impulsive SEP acceleration near the Hα flare site followed by diffusion through the closed coronal magnetic field lines (e.g., Perez-Peraza, 1986), these observations support a scenario of widespread shock acceleration high in the corona as shown schematically in Figure 4. Since the shock speeds may be as much as 1.7 times the speeds of the CME drivers (Gergely, 1984), the SEP source regions may be several Ro ahead of the CME. Support for SEP injection over a wide range of solar longitudes has been advanced by other authors (e.g., Mason et al., 1984).

Figure 4. Proposed schematic for the region of SEP acceleration and injection at shocks driven by fast CMEs. The shaded circle is the solar disk and the interplanetary field lines lie beyond the shock front.

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References