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Relative fluxes of shock and prompt peaks in SEP event time profiles

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Abstract

Peak fluxes are an important property of gradual solar energetic particle (SEP) event time profiles from both astro/heliophysical and applications perspectives. However, the peak flux in an event may occur at the event onset, or at the time of the interplanetary shock arrival (the ESP or energetic storm particles). This makes an important difference in the interpretation of the peak flux, and in any attempts to characterize or model it. This paper describes a study of SEP data sets from ACE, IMP-8 and GOES toward determining the relative properties of these peak fluxes for protons with energies near 1, 10, and 50 MeV. The results suggest that for gradual events with both peaks, the ESP peak often dominates at 1 MeV energies and is dominant about half the time at 10 MeV. Moreover, the prompt peak fluxes can be used to estimate the shock peak (ESP event) up to days ahead, especially in the lower energy range.

Keywords: Solar energetic particle events; Interplanetary shocks; Solar particle fluxes

1. Introduction

Time profiles of solar energetic particle events are important for space weather effects, but also for their use as diagnostics of the acceleration process(es) both at the Sun and in interplanetary space. It has been well over a decade since observational analyses were used to interpret SEP proton events detected near 1 AU as a combination of a moving coronal and interplanetary shock source, plus a possible contribution from flare-site accelerated particles (cf. Cane et al., 1988). The largest SEP events are the so-called gradual events that can last up to several days and are associated with fast coronal mass ejections (CMEs) arising from near the center of the solar disk as seen by the observer. These typically exhibit a time profile that shows a rapid rise to an initial ‘‘prompt’’ peak flux, within ~an hour of the solar event, followed in many cases by a second, sometimes higher intensity peak at energies <100 MeV at the arrival of the interplanetary shock. The current understanding of this second peak, called the Energetic Storm Particles or ESP event, is that it is composed of particles that have not yet become sufficiently accelerated in the shock’s turbulent magnetic field fluctuations to have escaped from their shock source (e.g., Kallenrode, 1996; Reames, 1999; Kahler, 2001a). This basic idea is further supported by the observation that the ESP event proton energy spectrum is softer than the spectrum in the prompt peak, and that the prompt peak particles can be highly collimated along the magnetic field, while the ESP particles are nearly isotropic (e.g., Reames, 1999).

The understanding of these peaks in SEP event time profiles is of considerable interest in the astrophysics and heliophysics disciplines because of the ubiquity of shock acceleration in space. The details of the acceleration process are still being explored both theoretically and observationally. The mechanism is thought to involve combinations of stochastic acceleration in wave fields, gradient drifts, and electric fields depending on the shock type and strength. For example, a high Mach number parallel shock may exhibit intense wave activity, while a nearly perpendicular shock has structure in the form of a foot and overshoot but negligible wave activity (e.g., Leroy et al., 1982). In fact most shocks are intermediate and exhibit some of each type of behavior, and they can also be

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non-planar and include the effects of different shock types at different locations along the same shock front. While most strong interplanetary shocks detected at the Earth tend to have intermediate shock normal angles due to the fact that the upstream field is a Parker Spiral, the shock normals themselves are generally close to radial. It is interesting in this regard to consider some of the ion hybrid simulations of shocks that have been undertaken (e.g., Krauss-Varban and Omidi, 1991; Giacalone, 2004). These can reproduce some of the details of shock-related wave fields and accelerated components of the background plasma ions. Yet these local simulations cannot take into account the fact that a moving SEP-event-generating shock has a long travel time relative to the acceleration time, and that particles accelerated at smaller radial distances can act as a seed population that moves ahead of the shock, constantly feeding it a subset of already suprathermal ions as it travels outward. Moreover, these local models cannot mimic the fact that an observer of a SEP event is sampling a sequence of different field connections to changing locations on the traveling shock front, rather than a single field line along which the shock moves. Nevertheless SEP events still represent one of the best ways to study in some detail the physics of particle acceleration by shocks in space. New models, taking into account both the large and small scale phenomenology underlying SEP event profiles, will ultimately improve our ability to sort out the various contributing factors. In the meantime, a better understanding of the profiles themselves is useful for both theoretical work and applications.

In this paper we present an analysis of gradual SEP proton event time profiles in order to investigate the differences in and relationship between the initially arriving or prompt flux peaks and the ESP or shock arrival-related increases. We are particularly interested in the >10 MeV SEPs, which are important from a space weather forecasting and technological effects perspective. It is worth noting that previous statistical studies of SEP events aimed at the problem of SEP flux prediction (e.g., Balch, 1999; Belov et al., 2005) do not always distinguish between peak fluxes associated with the promptly arriving protons and those that arrive with the shock. Fig. 1, reproduced from Reames (1999) suggests the importance of this distinction. The eastern event profile maxima are shock arrival-related because of the magnetic connectivity of the observer to the strongest part of the shock source, while western events are usually dominated by prompt flux peaks. In the case of events from near the center of the solar disk, either peak may dominate. This makes an important difference for any conclusions or physical inferences drawn from studies of peak fluxes and their solar associations. For example, a relationship might be expected between the prompt and ESP peak fluxes because both depend on the strength of the particular shock source. However, each shock, like each CME, has a unique radial profile of strength. Some are inferred to become stronger with radial distance if the CME starts slow, and others are inferred to be strongest near the Sun, where the prompt fluxes arise, and then decelerate (e.g., Yashiro et al., 2004 and references therein). The details of the shock size and the ambient solar wind into which it propagates are also relevant, as is the observer's magnetic connectivity to the shock. Here we examine over 200 gradual SEP event profiles that are sufficiently isolated to allow characterization of their prompt and shock-arrival fluxes. We find that there is a nearly linear relationship between the prompt and ESP peak fluxes at proton energies below 50 MeV that can be used in both model validations and in forecast applications.

2. Description of the data sets used

Three SEP data sets were used for the present analysis: advanced composition explorer (ACE) data obtained at the Sun–Earth libration point L1 with the EPAM (electron, proton and alpha monitor) from the Johns Hopkins Applied Physics Laboratory, Interplanetary Monitoring Platform 8 (IMP-8) data obtained in a 35 Earth radii geocentric low-inclination orbit with the CPME (Charged Particle Measurement Experiment) sensor from Goddard Space Flight Center, and the NOAA Geostationary Operational Environment Satellites (GOES) in geosynchronous orbit from the SEM (Space Environment Monitor) detectors. The online (http://www.srl.caltech.edu/ACE) ACE browse data were used to scan for and identify candidate events. Three classes of events were selected that fit the general types illustrated by Fig. 1, examples of which are shown in Fig. 2. Of the 213 events chosen, 55 were categorized as Type 1 events, showing both well defined prompt peaks or plateaus and shock arrival peaks, 45 were identified as Type 2, showing only prompt peaks, and 57 were identified as Type 3, showing only significant shock arrival peaks.

To obtain a reasonable statistical sample of events with ESP peaks, we focused on SEP proton energies of ~1 MeV, ~10 MeV and ~50 MeV, using ACE 5-min data at the lower energy (0.76–1.22 MeV) for the initial survey and event selection, 5–15 MeV IMP-8 data and 9–15 MeV GOES proton data for the next higher range profile of the selected events, and 9–15 MeV and 40–80 MeV data for the highest energy range profile. The time profile classification may change with energy range for the same event. For simplicity we refer in this paper to the three energies 1, 10 and 50 MeV to represent these ranges. We ensured that the presence of GOES and IMP-8 inside the magnetosphere was not a significant factor in the analysis by confirming that the profiles at the lowest energy available were similar to those seen on ACE with EPAM. We next determined the magnitudes of the peak fluxes by averaging the flux over small time intervals around the peak(s), approximately between half-maximum points as illustrated in Fig. 3 where a Type 1 event with both prompt and ESP peak fluxes is shown. This also yielded a date and time for each peak.

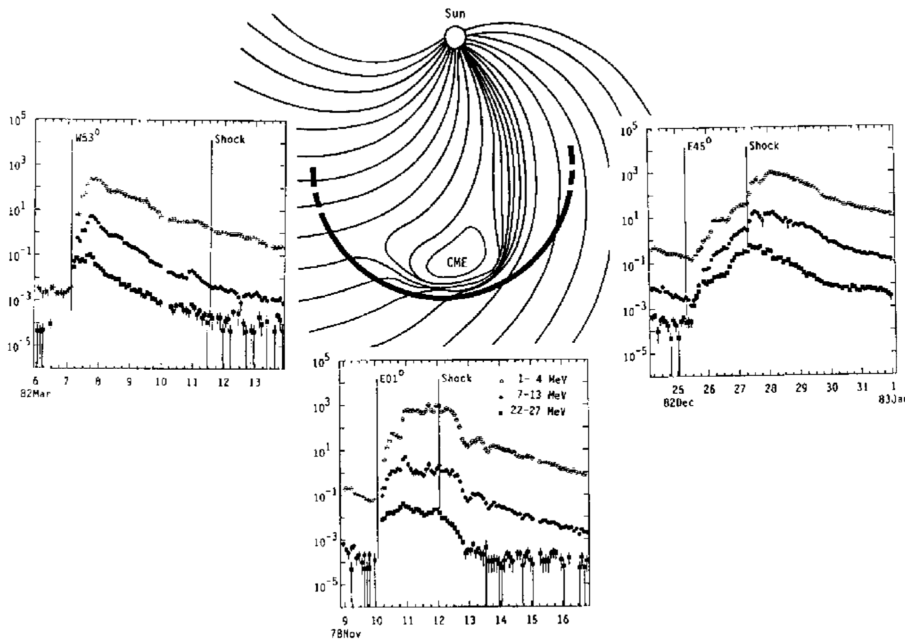

Fig. 1. Illustration from Reames (1999) of the spatial dependence of SEP proton time profiles surrounding their CME-generated shock source. The fact that the nose of the shock is the strongest part of source, and that the magnetic field connections to the observer (shown by the spiral field lines) channel the particles, combine to produce the different profiles. The timing of the peak flux with respect to the solar event (vertical lines on the left in the profiles) and the shock arrival at the observer (also indicated) is important to both SEP research and predictions.

Using the identified event times we examined the on-line CME catalogue of S. Yashiro (http://cdaw.gsfc.nasa.gov/CME_list), based largely on SOHO data but including GOES X-ray data, to find possibly related CMEs and flares. This enabled an analysis of the dependence of the different types of peak fluxes (prompt and ESP) on the solar longitude of the source region, the known organizing factor for SEP event profile types as well as for statistical studies of SEP event sources and fluxes. Because the CME results do not readily provide a point of origin, and the SEP events often have an associated significant flare, the temporally closest flare locations were used to provide a proxy for the solar event longitude, while the CME speed was used to estimate the event-related coronal/inner heliosphere shock velocity for the prompt peaks. For the shock velocities relevant to the ESP peaks, we used the on-line ACE MAG website shock data table at http://www-ssg.sr.unh.edu/mag/ace/ACElists/obs_list.html. Events without this supporting information available were not used in the analyses requiring knowledge of presumed source properties.

3. Results

Fig. 4 shows the solar longitude distribution, defined in the usual manner for SEP studies with respect to the central meridian of the disk, for both the prompt and ESP peaks, The prompt peak results include the statistics from both Type 1 and Type 2 events, while the ESP peak results include both Type 1 and Type 3 events (see Fig. 2). As might be expected from Fig. 1, the prompt peak distribution (Fig. 4a) has a greater concentration in the far western part of the disk, while the ESP peak distribution (Fig. 4b) has a significant central disk component. It is interesting that the ESP related solar source distribution appears almost bimodal, with a separate western concentration that is especially pronounced at higher energies. A distribution of this kind could result from an ESP source that is both stronger at the nose of the shock (creating the central concentration) and also at the quasiparallel shock flank where the local trapping of accelerated particles in the wave field may make stochastic acceleration more effective (see the typical shock normal angle geometry suggested by Fig. 1).

We next analyzed the relative importance of the prompt and ESP peak fluxes as a function of solar source (e.g., flare proxy) longitude and energy. Fig. 5 shows in graphical form the longitude versus the two peak fluxes for Type 1 events. As expected from previous studies the ESP peaks tend to dominate at the lowest energy range, and not all Type 1 events at $\sim$1 MeV show ESP peaks at the higher energies. However, at $\sim$10 MeV the ESP peaks still dominate about half the time. At $\sim$50 MeV the prompt peak dominates except in a few cases. Considering the importance of the ESP peak even at $\sim$10 MeV, it is necessary for modelers of SEP events to consider the physics of both the prompt and ESP peaks in their development schemes.

An examination of the dependence of the prompt peak fluxes on CME speeds near the Sun was carried out next. Reames et al. (1997) and Kahler et al. (1999) had found a clear dependence of SEP event peak fluxes on this parameter, although line-of-sight effects on the deduction of CME speeds from coronagraphs (especially not obtained

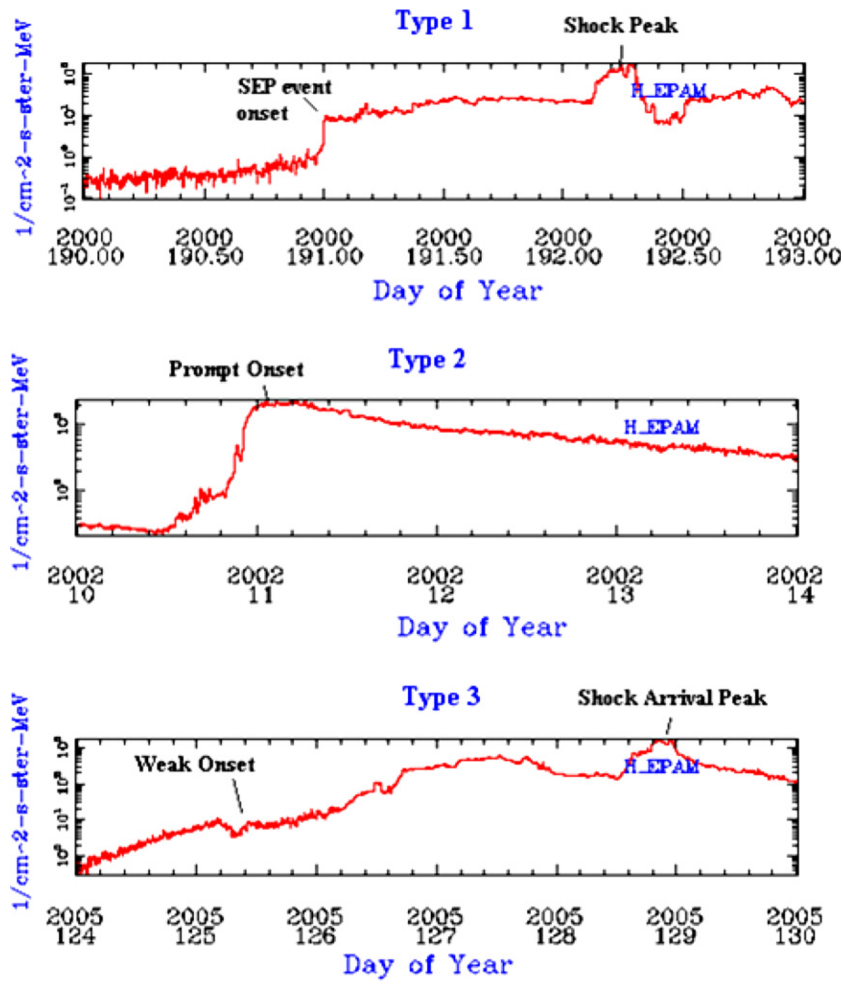

Fig. 2. Examples of the three types of SEP event profiles analyzed in this study, corresponding to those shown in Fig. 1. These plots of ACE 0.76–1.22 MeV EPAM data are from the ACE Science Center browser.

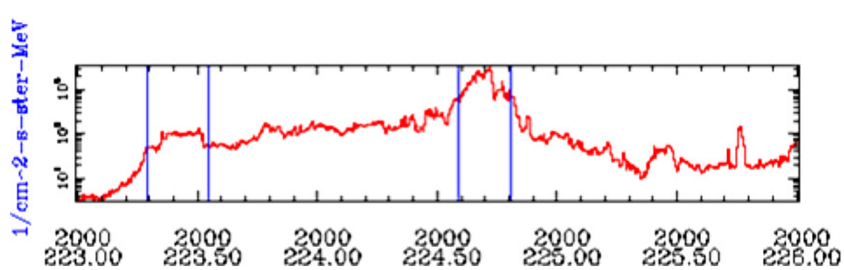

Fig. 3. Illustration of the selection of intervals used to determine the prompt (left vertical line pair) and ESP (center vertical line pair) peak fluxes in the Type 1 profiles (see Fig. 2).

in quadrature observations) represent a complication. Fig. 6 shows, for the three energy ranges under study, the relationship of prompt peak flux to CME speeds from the Yashiro CME catalogue (not corrected for line of sight effects, which requires some assumed geometry and modeling). The trend found earlier for a positive correlation of prompt SEP event peak intensities with CME speeds near the Sun is also seen here, although there is significant scatter. STEREO mission observations which will eliminate the CME line-of-sight velocity uncertainty should provide a better test of this relationship in the near future.

The corresponding comparison for the ESP peak fluxes is with in-situ shock velocities determined from ACE MAG and SWEPAM measurements collected by the MAG team. The result, shown in Fig. 7, suggests a dependence on local shock speed for the ESP peak fluxes as well. This is expected because the shock speed and strength (e.g., compression ratios) go together, although it also implies the presence of more particle-trapping magnetic turbulence or local shock drift acceleration at strong shocks. Note that there is a tendency for higher ESP peak fluxes to appear at increasingly higher shock speeds as the particle energy

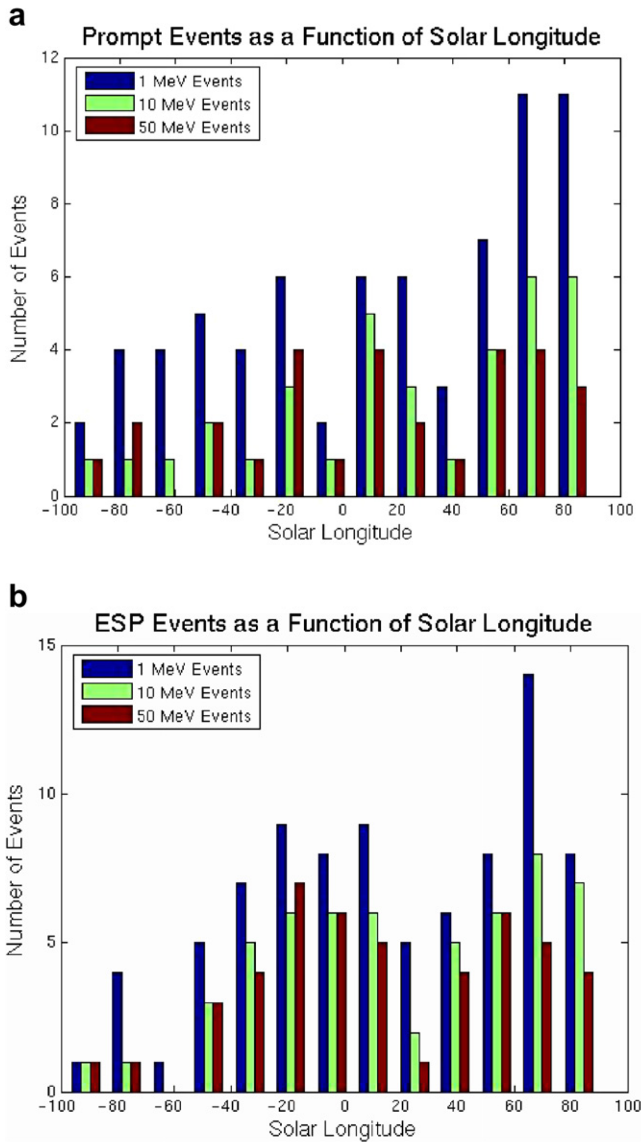

Fig. 4. (a) Solar longitude distribution (where zero degrees is the central meridian) of the source regions associated with prompt peaks used in this study. (b) Same as (a) but for the ESP peaks used in this study.

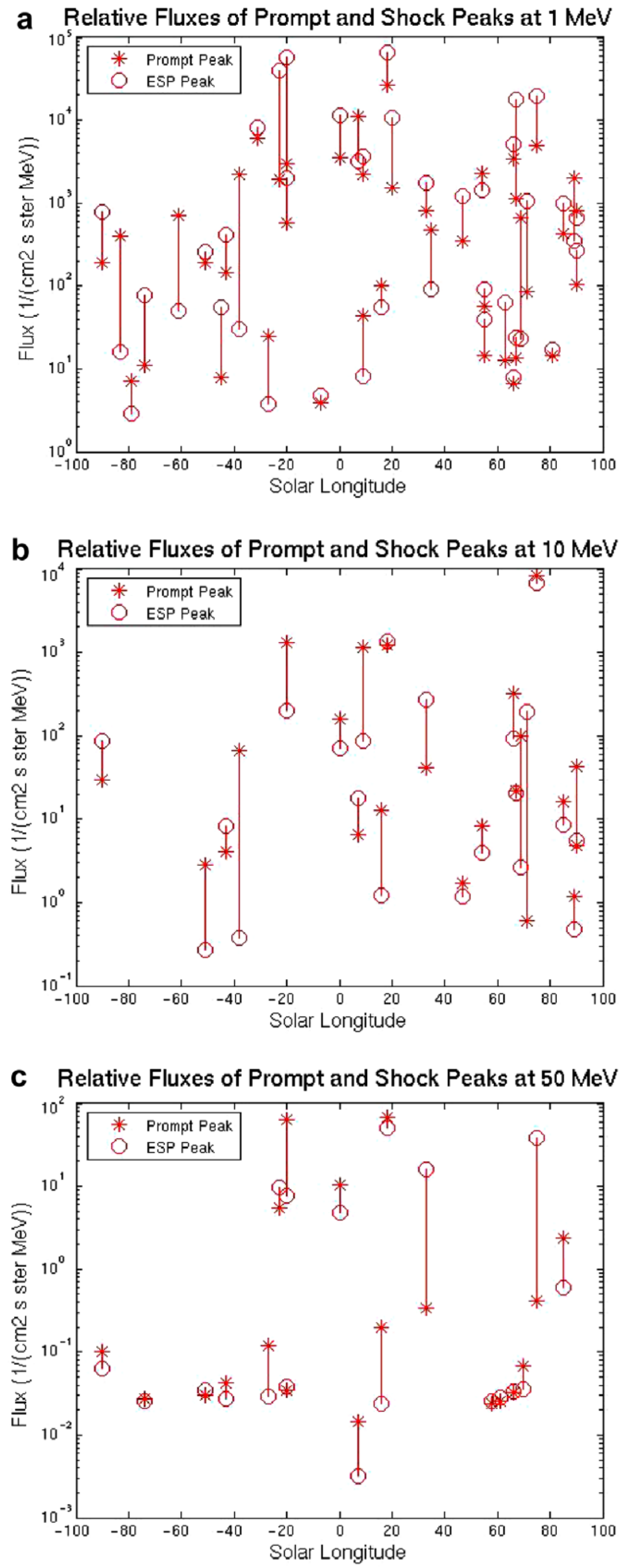

Fig. 5. Relative fluxes in the prompt and ESP peaks of Type 1 events for (a) the ~1 MeV energy protons, (b) ~10 MeV and (c) ~50 MeV. The ESP peaks tend to dominate at the lowest energy range, becoming less important as the proton energy increases, as expected. At ~10 MeV the dominant peak is equally likely to be prompt or from the ESP event.

increases. This is consistent with a hardening ESP spectrum with increasing shock speed.

Our last analysis has potential relevance for SEP event forecasting in cases where prompt fluxes are significant. If the prompt peak flux can give an indication of the ESP peak flux that follows it by ~1 to several days, it could provide a useful empirical method to alert users of that information to an expected event of significance. We analyzed the relationship between the prompt and ESP peak fluxes in the ~50 Type 1 profiles in our event data set in the three energy ranges. Fig. 8 shows the results. At every energy the prompt peak fluxes appears to give some indication of the following ESP peak fluxes, although the number of ESP events diminishes with increasing energy due to the relative softness of the ESP energy spectrum. An approximately linear relationship between the log peak fluxes can be

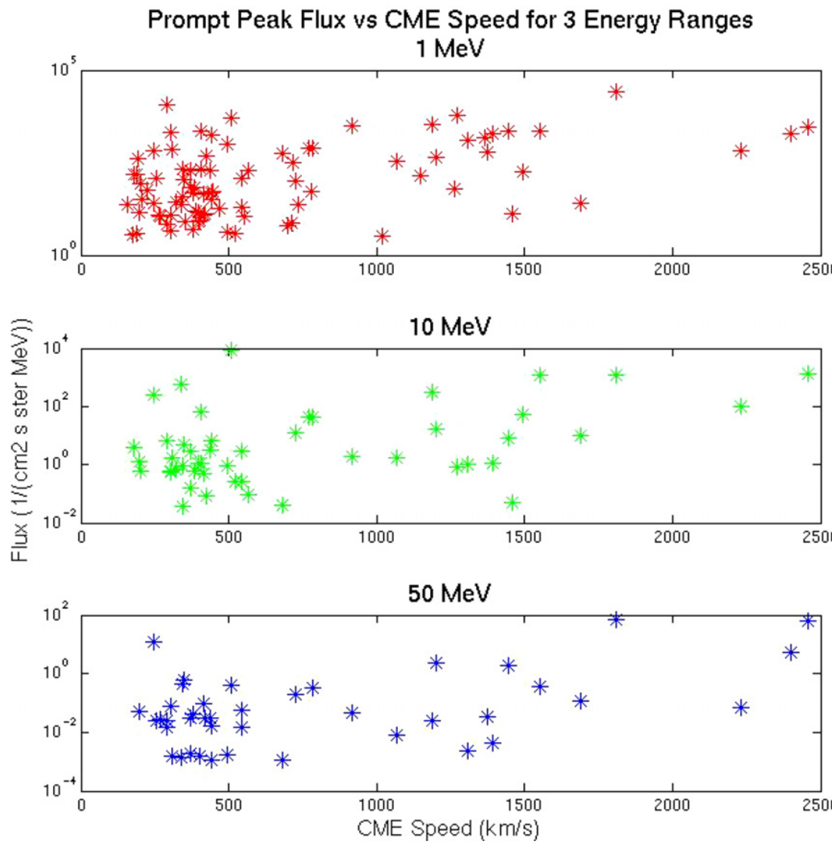

Fig. 6. Comparison of prompt peak fluxes with the associated CME speed observed near the Sun. The prompt particles are presumed to be generated by the CME shock when it is still in the corona, although suprathermal seed particles from flares may also be present.

defined at the lowest energies and is possibly present at 50 MeV. For the 1 and 10 MeV cases, the data are sufficiently numerous and ordered to allow lines to be fit with some confidence. The lines shown are

$$\log F_{\mathrm{esp}} = 0.98 \log F_{\mathrm{prmt}} + 0.080 \qquad (1\ \mathrm{MeV\ case})$$

and

$$\log F_{\mathrm{esp}} = 0.79 \log F_{\mathrm{prmt}} + 0.017 \qquad (10\ \mathrm{MeV\ case})$$

The scatter of points around the lines in Fig. 8a and b, fit with a standard least-squares method, is almost an order of magnitude, however. Our analysis has also neglected factors such as any pre-existing suprathermal ion fluxes (e.g., Kahler, 2001b), although in our search for well-characterized event profiles we avoided overly complex, multiple event periods. Still, the results suggest that for CMEs related to near-central meridian to western longitude sources at the Sun, the prompt flux gives an indication of the following ESP peak flux at both low and high energies. However, it provides a more constrained estimate at ~1 MeV than at ~10 MeV, which is sometimes considered the minimum energy of interest in SEP event forecasting. The results also suggest that even though the prompt peak fluxes and ESP peak fluxes come from quite different locations along the shock front, due to the Parker Spiral field mapping at early and later stages, the prompt flux can still be a useful measure of approaching shock strength.

4. Conclusions

The problem of interpreting the physics responsible for SEP acceleration through analyses of their event time profiles has been around for several decades, but our ability to use the information gained takes only occasional leaps. The study described here serves mainly to emphasize the importance of considering the prompt and ESP particles in a somewhat different light. By separating them in analyses that take into account their different associations with the near-Sun shock and the local shock, respectively, a better understanding of the sources of the largest fluxes in SEP events can be obtained. For example, here we considered that prompt peak fluxes should be related to CME speeds at the Sun, while ESP peak fluxes should be related to the local shock speed. We found that the two types of peak fluxes have somewhat different solar source longitude distributions. Nevertheless, when both peaks are present in an event, the prompt and ESP peak fluxes appear to be related, such that a strong prompt peak is followed by a strong ESP peak. This finding is not necessarily obvious given current thinking about prompt and ESP particle sources. A strong prompt event is considered the result of

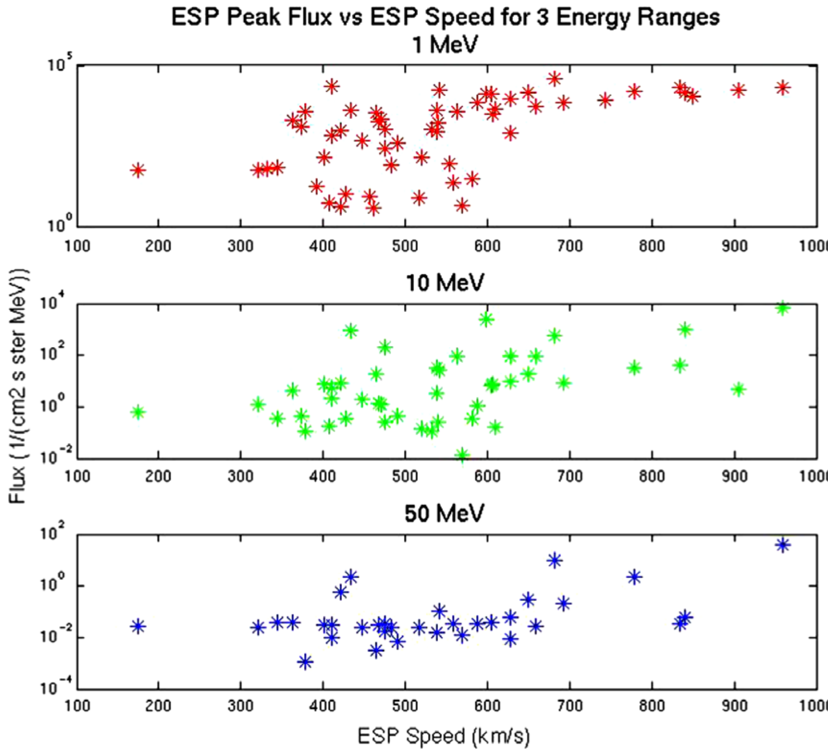

Fig. 7. Comparison of ESP peak flux and the speed at which the associated shock passes the observer. The strength of the shock as a source of accelerated particles is thought to be related to its speed as well as its field geometry.

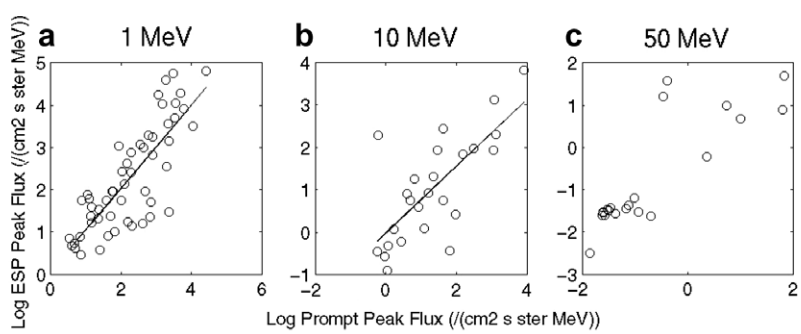

Fig. 8. Relationships of ESP peak fluxes to the prompt peak fluxes in the Type 1 events, suggesting that one can use the prompt peak flux to estimate the coming ESP peak flux. The number of points diminishes at high energies due to the relative softness of the ESP peak energy spectrum, which often causes the ESP peak to disappear at energies greater than a few 10 s of MeV. The equations for the least-squares-fit lines shown are included in the text. (a) ~1 MeV peaks, (b) ~10 MeV peaks, (c) ~50 MeV peaks.

the observer having an excellent magnetic connection to the nose of the shock of a fast CME when it is still close to the Sun – favoring a west limb CME. The ESP peak of the same event occurs with the passage of the shock nearly 90 degrees away at the Earth. The field connection for the two peaks thus samples very different portions of the shock as has been noted previously by Tylka et al. (2005) and others. Unless the fast shock is very broad, one might not expect the shock observed at Earth and the shock sampled near the Sun to both be strong sources. Indeed, some of the strongest prompt events do not have an important ESP component. For example our formula is not necessarily good for extreme events (e.g., Mewaldt et al., 2003). Nevertheless, the more typical large events appear to follow a trend whose physics should be better revealed by STEREO observations and global SEP event models.

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IMP-8 and GOES data used in this investigation. Use was made of the SOHO LASCO CME catalogue created by S. Yashiro on the CDAW website, and the ACE shock table created by C.W. Smith and Qiang Hu at Bartol and UNH. This work was supported by the National Science Foundation through CISM, the Center for Integrated Space Weather Modeling, a Science and Technology Center led by W.J. Hughes at Boston University, Grant ATM-0120950.

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