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To cite this article: S.W. Kahler *et al* 2017 *J. Phys.: Conf. Ser.* **900** 012011

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Flare magnetic reconnection fluxes as possible signatures of flare contributions to gradual SEP events

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Abstract. The primary sources of solar energetic (E > 20 MeV) particle (SEP) events are flares and CME-driven shocks. Some studies claim that even up to GeV energies solar flares are major contributors to SEP events. There are several candidate flare processes for producing SEPs, but acceleration in magnetic reconnection regions is probably the most efficient. Previous studies have relied on flare radiation signatures to determine the times and locations of SEP injections. An alternative approach is to use the amount of magnetic flux that gets reconnected during solar flares. The photospheric magnetic flux swept out by flare ribbons is thought to be directly related to the amount of magnetic reconnection in the corona and is therefore a key diagnostic tool for understanding the physical processes in flares and CMEs. We use the database of flare magnetic reconnection fluxes to compare these parameters with peak intensities of SEP events. We find that while sizes of 15 ∼25-MeV SEP events in the western hemisphere correlate with both CME speeds and reconnection fluxes, there are many cases of large reconnection fluxes with no observed SEP events. The occurrence of large reconnection fluxes accompanied by slow CMEs but no SEP events suggests that the CME shocks are the primary, if not the only, sources of high energy (E > 100 MeV) SEP events.

1. Introduction

It has long been established that there are two classes of SEP events [1-4]. Impulsive SEP events have small peak intensities, durations of hours, and substantially enhanced abundances of high-Z elements. Their solar associations are narrow white-light jets from magnetic reconnection regions, fast-drift type III radio bursts from electron beams, small impulsive flares, and well connected solar source longitudes of W20° to W80°. These SEPs are generally measured in the 2 to 5 MeV/nuc range where the intensities are highest and least susceptible to energy spectral variations [2]. The gradual SEP events are defined by their relatively high peak intensities, durations of at least a day, and abundances representative of the ambient corona, although in some events residual ions from previous impulsive events are also accelerated by the shocks. Their solar event associations are CMEs of widths W > 60° and speeds of Vcme > 900 km/s [5], slow-drift type II radio bursts, assumed to be produced in CME-driven shocks, and relatively long duration soft X-ray and Hα flares. The solar source longitudes can extend to beyond the east and west limbs as a result of the broad extent of the CME-driven shocks. The gradual SEP

event energy spectra can extend to several hundreds of MeV/nuc and are typically fitted by a double power law spectrum, expected from the theory of shock acceleration [6].

The division of all SEP events into two separate groups has never been completely accepted as a definitive paradigm by some SEP investigators. No one argues for CME-driven shocks as the sources of impulsive SEP events, but a flare contribution has often been invoked as a significant factor in some gradual events, particularly for those reaching GeV energies, known as ground level events (GLEs) because they can be detected with ground-based neutron monitors. All gradual SEP events are associated with fast CMEs, but both CMEs and flares arise in approximate spatial and temporal coincidence in solar energetic eruptive events, so parsing a flare contribution to an SEP event from the solar and SEP observations, taken separately or together, has been contentious. If a flare SEP contribution is present in a gradual event, one expects two signatures of that component. First, the elemental abundance ratios, such as Fe/O, should reflect the enhanced heavy ion abundances characteristic of the impulsive SEP event abundances. Second, the times of solar particle release (SPR), associated with the flare impulsive phase, should precede those of the shock-accelerated components, which arise in the subsequent development phase of the CME shock and type II burst.

2. Arguments for and against flare contributions to gradual SEP events

2.1. Flare contributions to ground-level events (GLEs)

The GeV protons of the GLE events travel from the Sun to 1 AU with minimal interplanetary scattering, so their solar injection times are readily determined from the 1 AU intensity-time profiles. The onsets of SEP events have been studied by Reames for 16 cycle-23 GLEs [7] and then for 30 well observed GLEs dating back to 1973 [8]. The GLEs were analyzed with plots of 1-AU arrival times versus c/v for particles with a wide range of speeds v to get the SEP injection times. The initial SPR times followed the onsets of type II bursts in all cases, as expected if all particles came from the type II shock and not from the preceding flare phases. Those initial SPR times were confirmed in a separate study of [9]. In addition, it was found that the SPR coronal heights increased with longitudinal distance away from the source, again as expected if only expanding coronal shocks were the sources of GLE SEPs.

The question of flare contributions to GLEs was directly confronted by Aschwanden [10] who compared the SPR profiles of Reames [8] with inferred flare impulsive-phase hard X-ray profiles for 12 non-occulted GLE sources. He found that 6 of the 12 SPR profiles overlapped in time with flare impulsive phases, which he took to be consistent with prompt GLE components from flares, as previously inferred by Vashenyuk et al.[11] for 35 large GLEs. Those authors found 29 out of 35 GLEs to have prompt components (PCs) defined by impulsive profiles, strong anisotropies, and exponential energy spectra. PCs were followed by delayed components (DCs) characterized by gradual profiles, moderate anisotropies, and power-law energy spectra. Other authors have found PCs in relatively fewer GLEs. Moraal and McCracken [12] reported double-pulse profiles in only three of 16 GLEs of cycle 23, but McCracken et al.[13] found high-energy impulsive enhancements (HEIs) averaging 21 minutes in length in 10 of 19 large GLES that they studied. All ten HEIs were associated with well connected ($\geq$ W24°) flare sources. Other investigators looking at selected GLEs [14-18] have also found two or more components, consistent with flare contributions.

2.2. Flare contributions to Fe/O ratios

Impulsive SEP events are distinguished by their enhanced Fe/O ratios, usually measured in the 2 to 5 MeV/nuc energy range [19]. Their relatively low intensities and durations of less than a day [20] would seem to preclude any direct contributions of these events to large gradual SEP events at energies of $\sim$ 25 MeV/nuc. However, remnant low-energy ions from previous impulsive SEP events could form a suprathermal seed population that would be favored by

quasi-perpendicular shocks [21], with resulting enhanced Fe/O ratios at ~ 25 MeV/nuc. The alternative interpretation favored by many investigators is that the impulsive SEP event occurs along with the CME eruption and directly contributes to the resulting mixed SEP event. Here again there are two possibilities for a direct flare contribution. First, the impulsive SEPs could interact with the CME-driven shock and be further accelerated to higher energies, particularly in quasi-perpendicular shocks. In the Particle Acceleration and Transport in the Heliosphere (PATH) model [22, 23] a direct flare SEP component extending to 1 GeV is assumed. The shock is transparent to the high-energy particles, but the lower-energy particles are further accelerated at the shock in addition to suprathermals of the solar wind. The preferred fraction of flare seed particles is $\sim 25\%$ [21, 23]. The second possibility is that the flare and shock make independent contributions to the mixed SEP event. In that case the flare SEPs are assumed to be more energetic than shock SEPs and a good magnetic connection is needed to observe such events.

Tylka et al.[24] found that only about one third of the event-integrated Fe-enhanced gradual events of their study had sources in a well connected longitude range. On the contrary, Cane et al.[25] found that the majority of the Fe-rich events of their 80 gradual SEP events occurred in the western hemisphere, which they took as evidence for flare contributions. As in their earlier work [26], they also found enhanced Fe/O ratios to occur more often with prompt SEP intensity profiles, reflecting an early flare injected component. However, the early occurrence of enhanced Fe/O ratios has been explained as an expected rigidity-dependent transport effect from self-amplified waves at shocks [3, 27, 28]. Mason et al.[29, 30] showed that for most western hemisphere SEP events, the Fe/O and O/He ratios were approximately constant in time-intensity profiles when plotted at appropriately scaled different energies, reflecting similar injection profiles near the Sun but different subsequent rigidity-dependent propagation characteristics. For observers not well connected to SEP source regions Dalla et al.[31] showed that the larger gradient and curvature drifts of Fe compared to O result in initially enhanced Fe/O ratios, which then decay in time. This drift effect would add to the transport effect from waves at shocks.

Further arguments against flare components are based on the fluence spectra of 16 GLEs compiled by Mewaldt et al.[32]. Those energy spectra were well fit by a double power-law shape expected from diffusive shock theory [33], and in no case was there a flattening at the high (~ 1 GeV) range that might indicate the presence of a flare component [34]. The slightly enhanced enrichments and highly-ionized charge states of Fe in the GLE events were consistent with shock acceleration beginning at heights of ~ 1.3 to 1.6 Rs and involving seed particles of remnant suprathermal ions of prior ^{3}He-rich flares.

3. Resolving the flare versus shock SEP debate with flare and CME signatures

It is clear from the preceding section that the GLE time profiles and Fe/O compositions of large SEP events have not settled the question of flare contributions to SEP events, and there remain two camps of investigators. A more simplified approach is to compare peak intensities of SEP events with associated flare X-ray peaks and CME speeds. An early comparison of logs of 2-MeV and 20-MeV peak proton intensities with associated CME speeds [35] yielded correlation coefficients (CCs) of 0.6-0.7 and were taken as evidence of shock acceleration of the SEPs. However, subsequent comparisons of peak SEP intensities with both CME speeds and flare X-ray peaks [36-39] have generally yielded comparable CCs of 0.4 to 0.7 for the CMEs and 0.3 to 0.6 for flares (Figure 1). While some authors [39] have inferred from these comparisons evidence of flare contributions to SEP events, the correlation between the CME speeds and associated flare X-ray peaks [40, 41] is acknowledged to be a confounding factor [39] in deducing whether or how much flares might contribute to SEP events.

Grechnev et al.[42] compared logs of E > 100 MeV proton fluences, corrected for source longitude, with associated logs of 35-GHz burst fluences observed with the Nobeyama Radio Polarimeter. By excluding from a "main sequence" of events four "proton-abundant" outliers,

which they considered as likely shock-source events, they derived a CC = 0.67 for 28 SEP events versus only 0.001 for the similar comparison with CME speeds, which they took as evidence of flare sources for those events. Cliver [43], however, pointed out that inclusion of the four proton-abundant events in the analysis reversed the results, now giving a CC = 0.09 for the 35-GHz burst fluences and 0.33 for the CME speeds. As a second line of argument, he compared the e/p ratios of 0.5-MeV electron peak intensities to those of E > 10 Mev protons for 22 well connected events of the [42] study with similar ratios of established impulsive-flare and shock-dominated SEP events to show that the [42] study events were consistent with the lower e/p ratios of the shock-dominated SEP events.
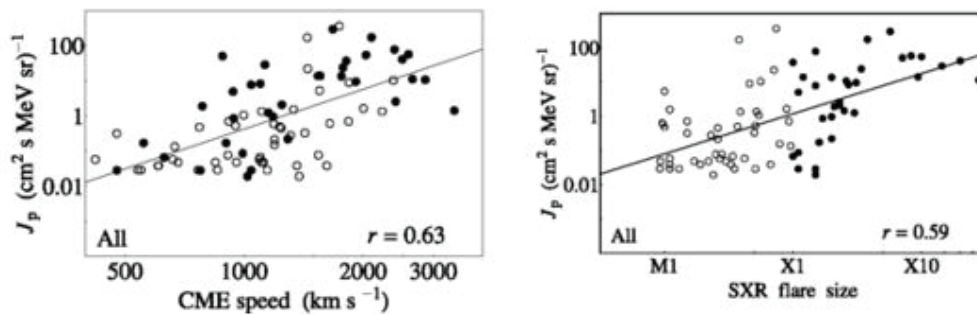

Figure 1. Comparison of peak GOES 15-40 MeV proton intensities of 81 SEP events versus CME speeds (left) and X-ray peak fluxes (right) showing the similarity of CCs for the two groups. Solid and open circles are M and X-class flare associations. From [36].

Fast CMEs seem to be a requirement for all gradual SEP events, but flares are not. Energetic (E > 50 MeV) SEP events have been observed following filament eruptions (FEs) associated with only C-class X-ray enhancements, apparently arising from late-forming CME shocks [44]. Do we find any events that might arise primarily or solely from flare injections only? On the assumption that the magnetic reconnection regions following solar eruptive events might be the flare sources of 25-Mev proton events, Kahler et al.[45] carried out a search for SEP events arising from well connected sources of soft X-ray arcades or metric noise storms. Of the 35 arcade/storm cases they investigated none was associated with a credible SEP event. More indirect evidence for at least a dominance of the shock contribution comes from a survey of major ($\geq$ M5) eruptive flares in cycle 24 [5]. The E $\geq$ 80-MeV proton events of that study were associated with a broad range of flare sizes, but the difference in average CME speeds Vcme of those proton events with and without large $\geq$ M5 flares was not large (2329 km/s versus 1724 km/s). Furthermore, large flares without SEP events had much lower average Vcme (1093 km/s), again consistent with a shock dominance for the sources of the SEP events.

4. Flare reconnecting magnetic fluxes as a better diagnostic for SEP event studies

Flare X-ray peak fluxes and fluences have been the tools of choice for comparative signatures in studying both the role of flares as sources of SEPs, as discussed above, and for forecasting SEP events (e.g., [46]). The X-ray observations (GOES full-Sun observations) are available in real time and readily quantified with a log-based C-M-X flux system, but they are a measure of thermal flare heating, and not of the energy release available for SEP acceleration. The active region (AR) magnetic flux is the energy source of solar eruptive events, so it provides a starting point for the quest of a better measure of flare energy. Nitta et al.[47] considered the AR unsigned magnetic fluxes associated with GLEs and other large SEP events, but found no AR property to be a discriminating factor for GLEs. However, proxies for the available active

region (AR) free energy can be deduced from algorithms using AR magnetic field maps, which are now available as SHARPs (Space-Weather active region patches) [48] based on magnetic images from the SDO/HMI instrument. Success in forecasting flares [49] and CMEs [50] based on AR magnetic flux algorithms suggests that we look not simply at the AR magnetic fluxes, but rather at the reconnecting fluxes in flares, the presumed source of any flare SEP production.
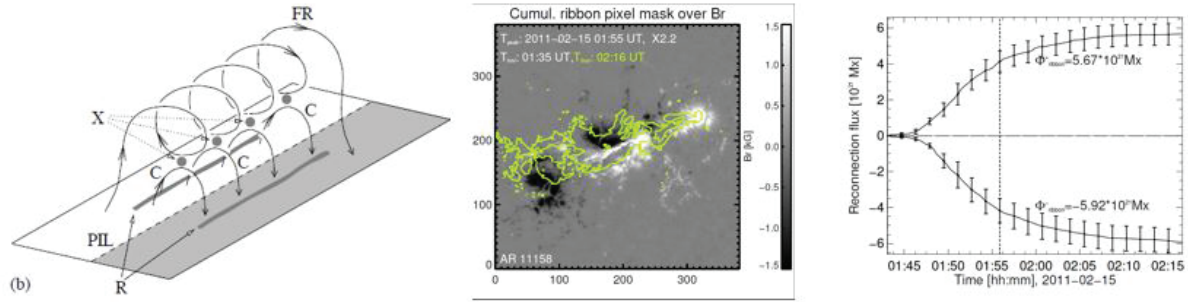

Figure 2. Basic concepts of the reconnecting flare magnetic fluxes. **Left**: Cartoon showing magnetic fields of erupting flux rope (FR) with reconnection X points and reconnection ribbons R lying along the polarity inversion line (PIL). From [54]. **Center**: Flare ribbon contours (green) overlay the SDO/HMI grey-scale radial component of the magnetic field of a 2011 flare example. **Right**: Plot of accumulated positive (top) and negative (bottom) reconnected flux for an example flare. The vertical dotted line marks the GOES X-ray peak time. Center and right figures are from [53].

Flare ribbons are emission structures that are frequently observed during flares in transition-region and chromospheric radiation. They typically straddle polarity inversion lines (PILs) of the radial magnetic field at the photosphere and move apart as the flare progresses. The ribbon flux, the amount of unsigned photospheric magnetic flux swept out by flare ribbons, is thought to be related to the amount of coronal magnetic reconnection. Previous measurements of the magnetic flux swept out by flare ribbons required time-consuming co-alignment between magnetograph and intensity data from different instruments, explaining why those studies only analyzed, at most, a few events. The launch of the Helioseismic and Magnetic Imager (HMI, [51]) and the Atmospheric Imaging Assembly (AIA, [52]), both aboard the Solar Dynamics Observatory (SDO), presented a new opportunity to compile a large sample of flare-ribbon events. Kazachenko et al.[53] have compiled a catalog of of flare-ribbon positions and reconnection fluxes, based on vector magnetograms from HMI and 1600 Å UV images from AIA (Figure 2). The catalog consists of 3137 > C1.0-class X-ray flares within 45° of disk center observed by the SDO from June 2010 to April 2016. We will use a subset of 406 unsigned magnetic reconnection fluxes from > C8.0-class flares to look for signatures of flare contributions to SEP events.

How well do the commonly used GOES flare X-ray peak fluxes and fluences compare with their associated AR unsigned reconnection fluxes? We compare the X-ray peak fluxes and fluences with the reconnection fluxes of the catalog on log-log plots in Figure 3. The linear correlation coefficients (CC) are 0.66 for the 406 flux peak events and 0.71 for 382 available fluence events, but there is a considerable scatter between the X-ray and magnetic flux values, indicating an uncertainty of at least 0.5 in the log values between the matched parameters. Kazachenko et al.[53] did a comparable fit for X-ray peak fluxes over their data base of all 3137 > C1 flares using the rank Spearman correlation r_s and found $r_s = 0.64 \pm 0.01$.
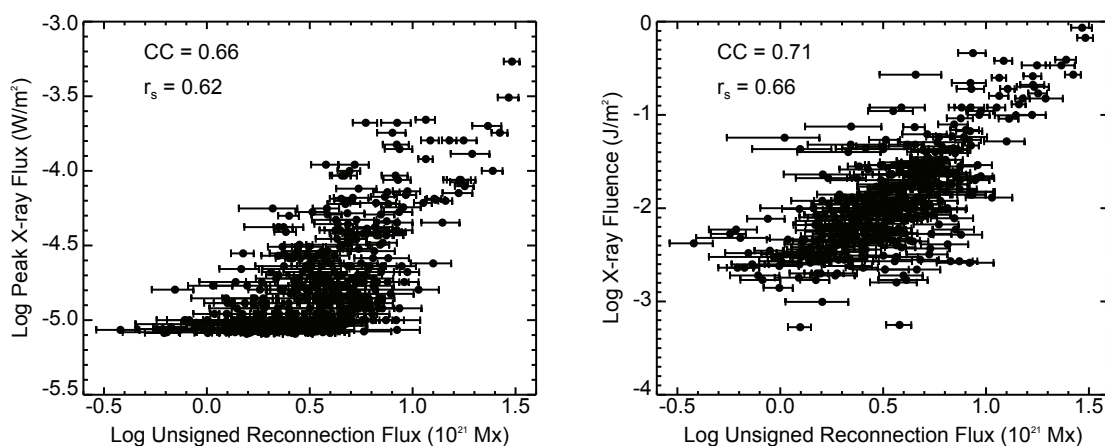
Figure 3. Log-log plots of the GOES flare peak X-ray fluxes (left) and fluences (right) versus the flare unsigned magnetic reconnection fluxes. Only flares of peak intensity > C8 (log > –5.1) are included in the catalog. The Pearson CC and Spearman r_s are indicated.

5. Data Analysis

The goal is to select flares at relatively well connected solar longitudes to search for associated SEP events that result mainly or solely from flare injections rather than from CME-driven shocks. Since the optimum well connected longitude range is $\sim$ W30° to W80° and the catalog extends only to W44°, we selected flares occurring in the range W20° to W44°, a total of 128 flares. We also look for CMEs associated with these flares, so a further preference is to avoid flare locations near disk center where the CME identifications and projected speeds are most prone to error [55]. We use an updated list of E > 25-MeV gradual SEP events observed at 1 AU [56]. There were 15 SEP events associated with the 128 selected catalog flares.

Each flare is characterized by separate positive and negative reconnection fluxes, which ideally should have the same magnitude. Here we use the total unsigned reconnection fluxes. For each flare we looked for associated CMEs in the LASCO CDAW catalog [57]. In two cases there were catalog data gaps, and in 59 cases there were no suitable CME associations, as expected from previous comparisons of flares with CMEs [58, 59]. Two of the authors did independent CME associations and resolved differences in four cases. Figure 4 shows the plots of the 126 reconnection fluxes versus the CME speeds, where we arbitrarily assign speeds of 40 km/sec to the cases of no CMEs to include those cases in the comparison. The dashed lines delimit the upper left quadrant where we look for candidate cases of high reconnection fluxes, indicating maximum flare reconnection energy, and low CME speeds, suggesting unlikely SEP production from shock formation. We not only find no SEP events in this quadrant, but also that all the 15 SEP events (red crosses) lie in the regions of highest CME speeds and are broadly distributed over the dynamic range of the flare reconnection fluxes.

We have examined the daily low-frequency (20 kHz to 13.8 MHz) dynamic spectral plots of the Wind/WAVES radio instrument [60] for each of the 59 flares without associated CMEs. With only 2 or 3 possible exceptions, there were no associated type III radio bursts with those flares, consistent with previous results for large non-eruptive flares [58]. We note that Reames et al.[19] found associated type III bursts for 95 of their 111 impulsive SEP events, so in the absence of a CME an associated type III burst would be a reasonable requirement in our search for candidate flare injections of 25-MeV protons. This reduces the optimum flare-SEP candidates in the upper left quadrant of Figure 4 to only 8 or 10 flares. For 11 of the 15 CMEs with SEP events we
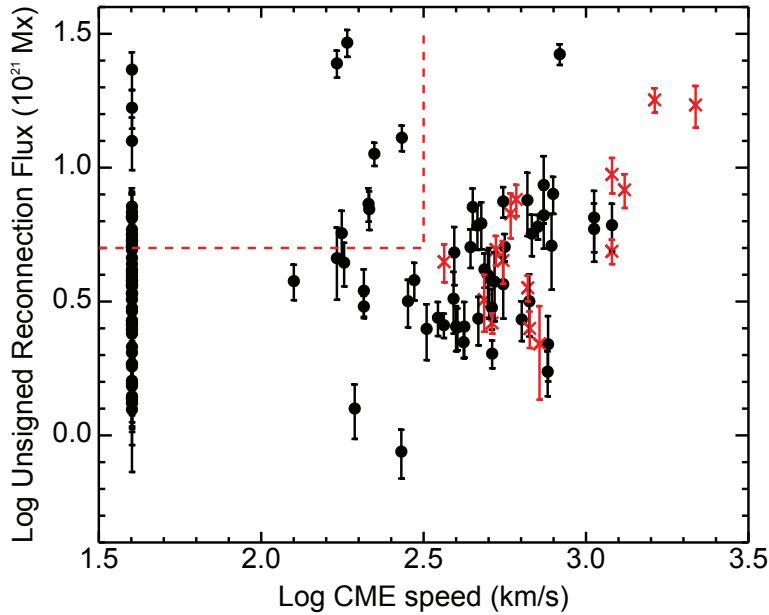
Figure 4. Log-log lots of the flare unsigned reconnection fluxes versus the CME speeds for the 126 flares. Black dots are flares with no associated SEP events, and red crosses are the 15 flares with SEP events. The flares with log CME speed = 1.6 are cases of no associated CMEs, for which Vcme was taken as 40 km/sec. The best candidates for flare SEP events are those in the upper left quadrant indicated by dashed lines. Plot units of the reconnection fluxes and CME speeds are 10^{21} Maxwells and km/sec, respectively.

found possible type II burst listings in the Wind/WAVES data. There were only metric type II bursts for three other CMEs, indicating likely shock acceleration for 14 of the 15 SEP events of the study.

The remaining SEP event, with no type II burst, on 30 September 2015, might be our best candidate for a flare source event. There were two candidate associated CMEs, the more likely of which had only a modest CME speed of 586 km/sec, but also an associated type IV radio burst, which often accompanies type II bursts. From SOHO/COSPIN and GOES observations, we found a peak 0.5 MeV/(> 10 MeV) e/p ratio of 200, right at the overlapping range of the high end of shock events and the low end of flare events [43]. The associated flare is a well connected (W42° S18°) M1.3 X-ray event with a typical reconnection flux of 6.73×10^{21} Mx (log = 0.83, Figure 3). However, the 0.5 MeV electron onset in the COSPIN observations is $\sim$ 1600 UT and the 25 MeV proton onset at 1900 UT, both more than 5 hours after the 1049 UT flare X-ray peak, so our assumed solar association is tenuous. Thus, we do not find in this data set a good candidate flare-source SEP event.

Finally, we compare the SEP peak 25-MeV proton intensities of each SEP event with their corresponding flare reconnection fluxes in Figure 5. When no associated SEP event was observed, we use the approximate instrument background value of 1×10^{-4} p/(cm² s sr MeV). There is a weak trend for larger SEP peak intensities to scale with the reconnection fluxes, but in each plot range the cases of no SEP events are dominant.
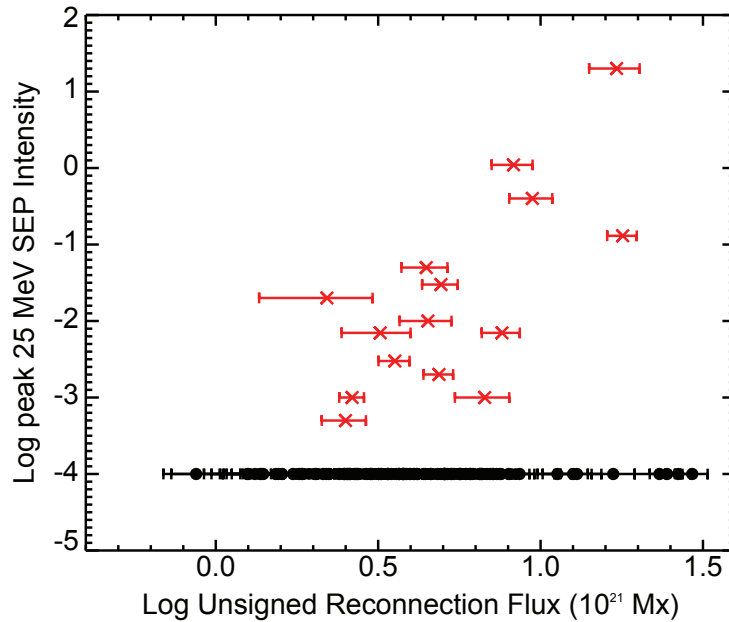
Figure 5. Log-log lots of the peak 25-MeV SEP intensities in protons/(MeV cm^2 sr sec) versus unsigned reconnection fluxes. Cases of no observed SEP events are shown with black dots at instrumental background values.

6. Discussion

The goal of this study has been to use a new quantitative measure of flare magnetic-reconnection energy to search for $\geq$ 25-MeV gradual SEP events that might have a sole or dominant flare contribution rather than only the shock contribution assumed in the two-class SEP event paradigm. The flare X-ray peak or fluence is the product of an AR emission measure distribution in temperature that reflects the thermal flare heating and may not be relevant to the nonthermal process(es) involved in SEP acceleration. We have seen in Figure 1 that the X-ray signatures do not differ substantially from CME speeds in their correlations with SEP event peak intensities.

We found good correlations between logs of the X-ray flare peaks and fluences and logs of the flare reconnection fluxes. However, if the conjectured flare SEP injections arise from magnetic flux reconnection, then the reconnection fluxes may be the best available signatures of that acceleration process. We have compared the flare reconnection fluxes with associated CME speeds to attempt to isolate SEP events with strong flare components (Figure 4), but except for one case the gradual SEP events are characterized by fast CMEs with associated type II bursts expected from the shock-source scenario for those events. A questionable flare/CME association characterizes the one remaining SEP event.

Our result constitutes weak evidence against the flare-SEP concept. The flare longitudes of the study (W20° – W45°) are optimized for magnetic field measurements and are not well suited for good magnetic connections to Earth or for CME detections and speed measurements. The event numbers (15 SEP events and 126 flares) are small, and nearly half of the flares have no observed associated CMEs or type III bursts. Figure 4 could be construed as indicating a flare reconnection contribution to SEP events, but most flares with similar reconnection fluxes are not associated with SEP events. An inherent limitation of this kind of study is that the reconnection fluxes correlate with flare peak X-ray fluxes (Figure 3), which correlate with both

CME speeds and SEP intensities (Figure 1).

The question of flare contributions to gradual SEP events may be better addressed by simply requiring the demonstration of one good example of an SEP event with no associated fast CME and shock. When have we ever seen such an event? All the arguments reviewed in Section 2 claim the existence of a flare contribution in addition to another, usually shock-based, contribution. The enhanced Fe/O ratios early in the SEP events can be explained by rigidity-dependent propagation, and the claimed GLE PCs have exactly the properties of initially harder energy spectra and higher anisotropies that one expects from the propagation effects of single shock-accelerated injections. Why should the alleged flare-based PC occur only in conjunction with the shock-based DC in GLEs?

Finally, we should demand more theoretical insights into the mechanism(s) and observational consequences of the presumed flare SEP acceleration process. Is there necessarily an elemental abundance enhancement, as is seen in impulsive SEP events? Does the acceleration process occur in coincidence with the hard X-ray impulsive phase of the flare? Where in the corona, in what kind of magnetic configuration or topology, and with what timescale does the flare SEP acceleration and injection to space occur? In view of the considerable recent progress in detailed modeling of type II emission [61, 62] and SEP injection from coronal shocks [63], the vague attributions of a SEP flare acceleration process remain at best primitive.

Acknowledgments

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