Mixed particle acceleration at CME-driven shocks and flares

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[1] A recent study of *Cane et al.* [2003] showed that in some intense SEP events, the time-intensity profiles exhibit two peaks, with an earlier one having a high *Fe*/*O* and a later one with a low *Fe*/*O* ratio. They suggested that these two-component events are due to CMEs and their accompanying flares occurring together, with the first peak being flare-related and the second peak being CME-driven shock related. In this paper, we develop a model which examines particle acceleration and transport when both flares and CME-driven shocks are present. We study time-intensity profiles for three different scenarios: a pure shock case, a pure flare case and a shock-flare-mixed case. Using reasonable estimates of the relative timing between CMEs and associated flares, we find that a large portion of the flare accelerated material is subject to absorption and re-acceleration by the CME-driven shock. Consequently, the time intensity profile for the shock-flare-mixed case shows an initial rapid increase, owing to particles accelerated at the flare and followed by a plateau similar to that of a pure shock case. **Citation:** Li, G., and G. P. Zank (2005), Mixed particle acceleration at CME-driven shocks and flares, *Geophys. Res. Lett.*, *32*, L02101, doi:10.1029/2004GL021250.

1. Introduction

[2] Solar flares and coronal mass ejections (CMEs) are arguably the two most catastrophic solar phenomena observed and are believed to be the origin of impulsive and gradual solar energetic particle (SEP) events respectively. In the current paradigm, [see, e.g., *Reames*, 1999], impulsive events are usually characterized by an enhanced $^3He/^4He$ ratio, up to 1000 times of that of the coronal value, a high *Fe*/*O* ratio (e.g., 0.3–5) and high charge states of heavy ions, e.g., $Q(Fe) > 16$. These are believed to be reasonably representative values for accelerated material at the flare site. In contrast, gradual SEP events usually have a lower *Fe*/*O* ratio close to 0.134, fewer charged states for heavy ions (e.g., $Q(Fe) \sim 14$), which corresponds to a temperature of 2∼3 Mk, and is thus believed to be of coronal origin.

[3] While such observations have provided a practical classification of SEP events, cases have been observed that tend to exhibit mixed characteristics corresponding to both gradual and impulsive events. Indeed, *Cane et al.* [2003] have studied 29 intense solar particle events in the energy range 20–80 MeV/Nuc between 1997 and 2001 and found that four of these events exhibit double peaks in the intensity profile with the first peak corresponding to a high Fe/O ratio and the second to a low Fe/O ratio. The second peak coincided with the passage of the interplanetary shock. These observations lead *Cane et al.* [2003] to conclude that in some large solar energetic particle events, two distinct components, corresponding to solar flare accelerated material and CME accelerated material, are present simultaneously. However, alternative explanations involving a seed population consisting of remnant flare material, together with particle acceleration at a perpendicular shock also exist (A. J. Tylka et al., Elemental composition at high energies in large gradual solar particle events, submitted to *Astrophysical Journal*, 2004). To identify whether two distinct energetic particle components are present in large SEP events, a clear understanding of the temporal relationship between CMEs and associated solar flares is required. *Zhang et al.* [2001] studied four CME events in detail with the help of the telescopes C1, C2 and C3 of LASCO and X-ray data from GOES. They found a strong temporal correlation between the increase of CME speed and the increase of flux of the associated flares. They were able to show that the main CME acceleration and the main energy release of associated flare occur almost simultaneously in time [see also *Zhang et al.*, 2004]. Their study suggests that CMEs and flares are not distinct processes, rather, they correspond to the same physical process and are merely different manifestations of it. If indeed, CMEs and associated solar flares occur at approximately the same time, then we would expect to see some interaction between processes associated with these two events. For example, one might expect that some particles accelerated by solar flares, which possess the elemental and isotopic characteristics of flare material, may undergo re-acceleration at the CME driven shock. Of course, this argument is based on the assumption that there are open field lines at the flare site which allow flare accelerated particles to propagate out to a CME-driven shock or into the interplanetary medium. *Cane et al.* [2002] studied the correlation between flares in >20 MeV solar proton events and type III radio bursts and argued that since the radio frequency f is related to the ambient electron density through $f/kHZ = 9\sqrt{n_e/\mathrm{cm}^{-3}}$, the detection of type III radio emission starting from frequencies above 100 MHz suggested that open field lines beneath CMEs down to 0.5 solar radii must exist. In this work, we present a simple model and study the consequences of having both flares and CMEs as the source for SEP events.

2. Model Description

[4] We discuss our model and the assumptions behind the simulation in this section. First, we assume a CME and a flare go off at the same time. The particle acceleration period due to the flare is set to be 1000 seconds, which is in agreement with the rise phase of the X-ray profile of the flare [*Zhang et al.*, 2001]. The evolution and propagation of the CME-driven shock and the corresponding particle acceleration is followed using a model we developed

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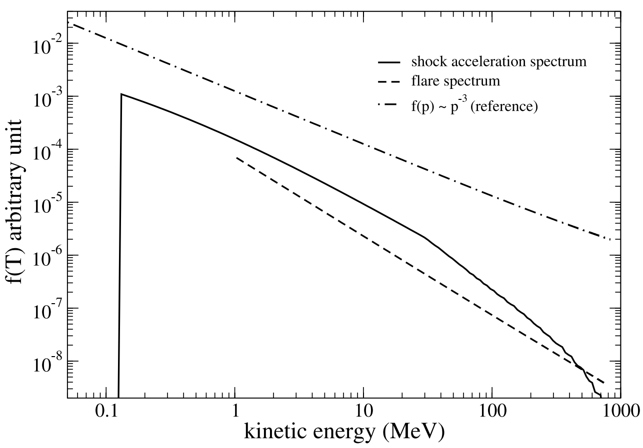

Figure 1. Plots illustrating the initial flare particle spectrum (dashed line) and the time-integrated spectrum of particles escaping from the CME-driven shock (solid line). A p^{-3} power law is plotted for reference (dot-dashed line). See text for details.

previously. Readers are referred to *Zank et al.* [2000], *Rice et al.* [2003] and *Li et al.* [2003, also Acceleration and transport of heavy ions at coronal mass ejection drive shocks, submitted to *Journal of Geophysical Research*, 2004, hereinafter referred to as Li et al., submitted manuscript, 2004] for further details of the model.

[5] The shock is assumed to start at 5 solar radii. This is based on timing studies [e.g., see, *Tylka et al.*, 2003] which showed that particle acceleration begins when the shock is located at 3 $\sim$ 8 solar radii. Another key parameter of the simulation is the relative number of energetic particles accelerated by the solar flare compared to that of the CME-driven shock. Observations by RHESSI can be used to estimate the energy released by the energetic particles that precipitate to the surface of the sun (e.g., the total energy released by a large flare can reach $\sim 10^{31-32}$ erg [*Lin et al.*, 2002]). However, the percentage of energetic particles escaping along open field lines is unknown. Furthermore, CMEs are usually much wider than flares. For example, *Burkepile et al.* [2004] found an average angular width of 50 degrees. Flares, on the other hand, are usually very angularly confined, often less than 10 degrees [see, e.g., *Svestka*, 1976]. In this work, to facilitate the simulation, we take the ratio of flare accelerated particles to CME accelerated particles to be 1:2. However, changing this parameter to either 5:1 or 1:1 only changes the result slightly.

[6] Using RHESSI, one is able to directly invert the solar flare hard X-ray spectrum to obtain the spectrum of the parent electrons [*Johns and Lin*, 1992]. Similar techniques can be used to invert the gamma ray continuum to obtain the ion spectrum and we expect ions and electrons have similar spectra. In this work, we assume a $\sim p^{-4}$ spectrum for flare accelerated particles with a minimum momentum $p_{\min}$ = 43 MeV/c and a maximum momentum $p_{\max}$ = 1400 MeV/c.

[7] An important feature of the simulation is the absorption and re-acceleration of energetic particles by the traveling CME-driven shock. Particles, released from the flare site and/or escaping from the CME-driven shock front, will experience only occasional pitch angle scattering, and their transport obeys the Boltzmann equation. Because of pitch angle scattering, particles released from the flare site or having escaped from the CME-driven shock earlier may reverse their propagation direction and move towards the sun. As the shock is propagating out, particle absorption at the shock may occur. Once a particle is trapped within the shock complex, it will be re-accelerated diffusively, whether or not it was previously a flare accelerated particle or a shock accelerated particle. This absorption and re-acceleration of particles originating either at the flare or the CME-driven shock will smear out the differences between a pure flare event and a pure shock event. As a result, we expect to find events with a shock-like time-intensity profile, but flare-like composition. This, to some extent, is what *Cane et al.* [2003] observed. Of course, not all particles propagating back to the shock will be absorbed and re-accelerated. A particle can only be absorbed if there are resonant waves with wave vector k satisfying (see, e.g., Li et al., submitted manuscript, 2004),

$$k \approx \gamma m \Omega |\mu| / \mu p. \quad (1)$$

Here, $\Omega = (Q/A)eB/\gamma m_p$ is the local ion gyro-frequency, and μ the particle pitch angle. Since the minimum wave number $k_{\min}(t)$ and the maximum shock acceleration momentum $p_{\max}(t)$ at time t satisfy equation (1), particles with $p > p_{\max}(t)$ are not subject to scattering by the turbulence and thus do not feel the presence of the shock.

3. Results and Discussion

[8] As stated above, in the simulation, we assume N(flare): N(CME) = 1: 2, where N(flare) represents the total accelerated particle number by flare and N(CME) represents the total accelerated particle number by CME-driven shock. The spectra of particles accelerated by the flare and the CME-driven shock are plotted in Figure 1. The dashed line is for the flare particles, taken to be $\sim p^{-4}$. Note that it only lasts for the first 1000 seconds of the simulation. Since the shock starts at 5 solar radii, we assume a 30 minute delay (corresponding to the propagation time of the CME from the surface of the sun to 5 solar radii) for the shock propagation. Thus the flare process is completed 12 minutes before the shock acceleration mechanism initiated. Our simulation results will depend on the time between the end of the flare process and the formation of the CME shock. A reasonable estimate of such an interval requires better understanding of both processes (see, e.g., *Cliver et al.* [2004, Figure 9], which illustrates the temporal relationship between flare particle acceleration and shock formation), and in this work, we simply take this interval as a parameter. We find that noticeable changes to our result only occur when the gap is increased to above 40 minutes.

[9] The solid line is the time-integrated particle spectrum for the CME-driven shock. It represents the accelerated particles that escape from the CME-driven shock during the propagation of the CME-driven shock from the Sun to 1 AU. As a reference, a p^{-3} line is also shown in the plot. At the high energy end, the time-integrated spectrum of particles accelerated by CME-driven shocks is softer than p^{-4}, reflecting the fact that as the shock propagates and weakens, the maximum attainable particle energy decreases. At the low energy end, the time-integrated spectrum is convex with parts similar to p^{-3}, reflecting the fact that it is more

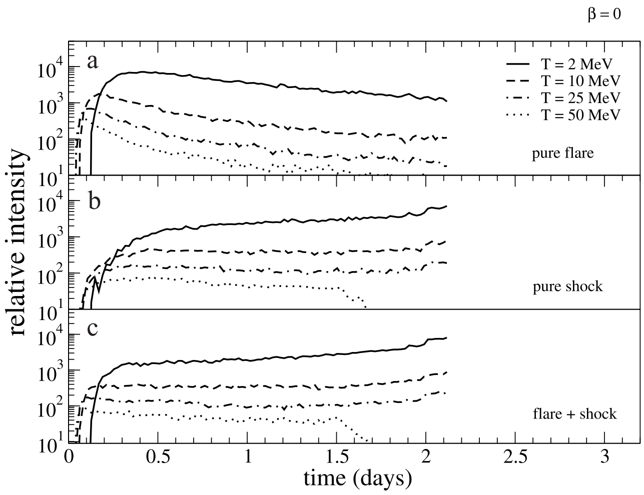

Figure 2. Time intensity profile for protons: (a) particle acceleration due to a pure flare source, (b) particle acceleration due to a pure shock source, and (c) assumes a mixed source. See text for details.

difficult for particles of lower energies to escape from the shock.

[10] In all simulations, the mean free path λ for particles propagating in the interplanetary medium is taken to be of the form [*Li et al.*, 2003],

$$\lambda = 0.4\mathrm{AU}\left(\frac{pc}{1\mathrm{GeV}}\right)^{1/3}\left(\frac{r}{1\mathrm{AU}}\right)^{\beta}. \tag{2}$$

Figures 2 and 3 plot time intensity profiles for protons. Figure 2 corresponds to β = 0 and Figure 3 corresponds to β = 2/3. Figures 2a and 3a assume particle acceleration due to a pure flare source. Figures 2b and 3b assume particle acceleration due to a pure shock source, and Figures 2c and 3c assume a mixed source of both a shock and a flare. In both Figure 2a and Figure 3a, the time intensity profile for the "flare-only" case shows an abrupt rise followed by a decay. However, the decay phase, especially for the 2 MeV curve, is less sharper than that observed in impulsive flare events. This is because we assumed the source for a "flare-only" case lasted 1000 seconds and that the flare particles are evenly distributed within this 1000 seconds. Furthermore, the assumed p^{-4} spectra might be harder for a flare, and finally the mean free path we assumed in equation (2) is from our earlier modeling of CME events. The energy dependence of equation (2) tends to ensure that low energy particles take a long time to reach 1 AU.

[11] Figures 2b and 3b correspond to the "shock-only" case. Compared to the "flare-only" case, it is clear that the traveling shock, which is neither spatially nor temporally confined, leads to a much slower rise of the intensity profile. Consider now Figures 2c and 3c. These are the "flare + shock" case. Firstly, at early times, as we expected, the intensity profile resembles the "flare-only" case. These are particles that were accelerated at the flare site, then propagate to 1 AU faster and were not absorbed by the shock. At later times, the contribution from the shock becomes more pronounced. The contribution comes from two populations, these being particles that were injected from the ambient solar wind and accelerated at the traveling shock, and particles that were accelerated at the flare but have been absorbed and re-accelerated by the shock. The latter particles, once absorbed, will behave like those particles that originate at the shock. Thus, at late times, we expect the intensity profile of the "flare + shock" case to behave like that of the "shock-only" case. However, the composition will be a mixture of flare material and ambient solar wind.

[12] To better understand the shock re-acceleration of flare particles, we have, in the simulation, kept track of those particles that originated from flare. The time intensity profiles of these particles are plotted in Figure 4. Figure 4a is for β = 0, and Figure 4b is for β = 2/3. From Figure 4, it is clear that particles of different energies behave differently. The intensity profile of high energy particles, for example, that of T = 50 MeV behaves very similarly to the "flare-only" case (Figures 2a and 3a). This is due to two reasons: first, particles with higher energies travel faster and are thus more difficult for the shock to catch. Secondly, as the shock propagates into the solar wind and weakens, it can no longer generate turbulence at small enough wave numbers to

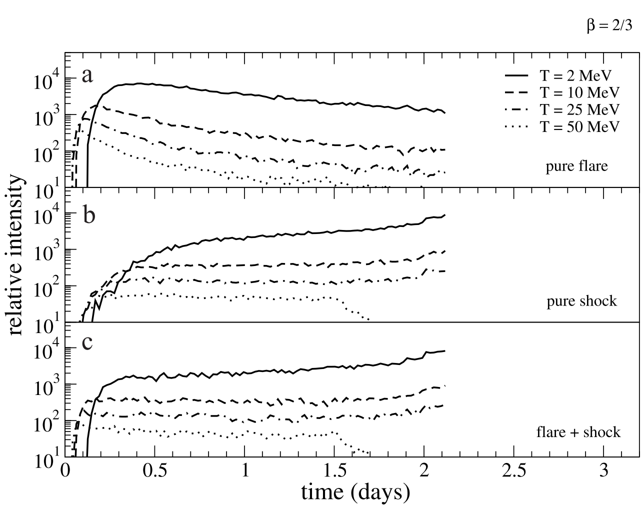

Figure 3. Same as Figure 2, but with β = 2/3.

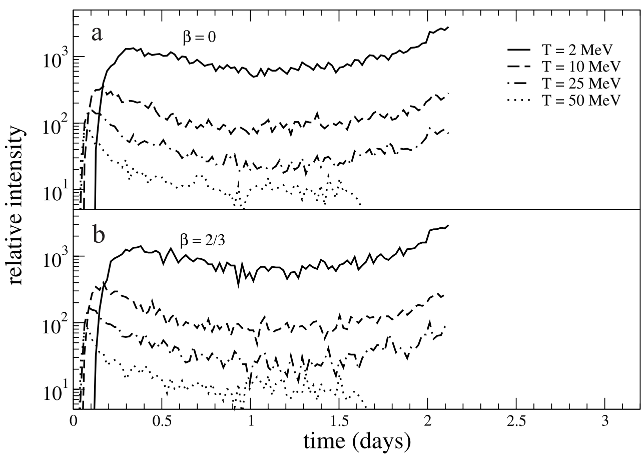

Figure 4. Time intensity profile of particles originated only from a flare, but subject to absorption and reacceleration by a propagating CME-driven shock: (a) β = 0 and (b) β = 2/3.

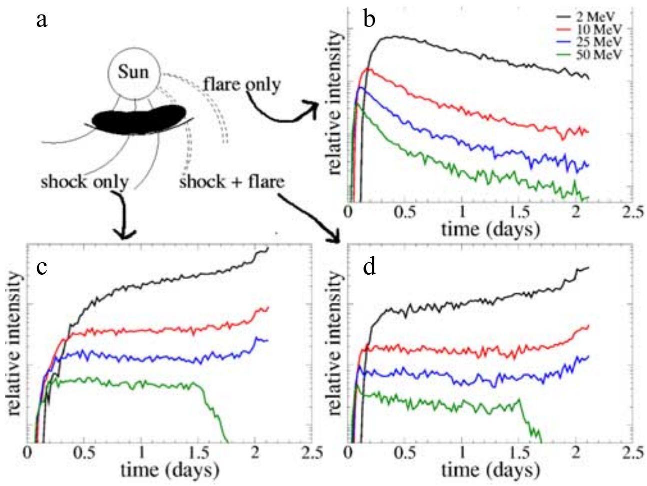

Figure 5. Cartoon to show the observational signature of SEP events as a function of the spacecraft longitude. See text for details.

resonate with particles of high energies. Thus, to these particles the shock is "transparent". Consequently, the time intensity profile looks more like that of the "flare-only" case. For low energy particles, however, this is not the case. The intensity profiles for T = 2 MeV and T = 10 MeV resemble those of the "flare-only" case at early times and the CME-driven shock case at later times. This of course is what we expect since the shock is still able to accelerate particles to energies of 10's of MeV at relatively late times. Thus flare particles at this energy are still subject to absorption and re-acceleration by the shock.

[13] If CMEs and flares are indeed not distinct processes, but rather different manifestations of the same process, then the traditional paradigm for SEP events requires some modification. The cartoon shown in Figure 5 illustrates a possible scenario for a large SEP event. Here, contrary to the traditional picture where gradual SEP events are due to a CME-driven shock solely and impulsive events are due to flares solely, particles from both the CME and its associating flare co-exist. Depending on the longitude of the spacecraft (whether it is well connected to the CME-driven shock or the flare), the same event will exhibit different behaviors. For example, if a spacecraft is only connected to the flare, then the observed time intensity profile would be similar to that of Figure 5b. If a second spacecraft is connected to both the CME-driven shock and the flare, then the observed time intensity profile would be similar to that of Figure 5d. Finally, if a third spacecraft is only connected to the CME-driven shock, then the observed time intensity profile would be similar to that of Figure 5c. The scenario shown as in Figure 5 might be of interest to the STEREO mission. Scheduled to launch dual spacecraft in early 2005, the STEREO mission may provide an excellent opportunity to examine the validity of the new paradigm and the relationship between solar flares and CMEs.

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