Multiple CMEs and large gradual SEP events

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Gradual Solar Energetic Particle events (SEPs) are now believed to be associated with shocks driven by Coronal Mass Ejections (CMEs). As CMEs propagate out from the Sun, particles are accelerated at the shock front, reaching energies to 10's of MeV and occasionally $\sim GeV$'s. Understanding the time intensity profiles of these gradual events and the spectra of the accelerated particles are of practical importance to, for example, manned spacecraft program since these particles are the No. 1 space-weather hazard. Recently, there are observational indications that large gradual events usually happen when two or more CMEs occur closely. In this work, we investigate particle acceleration at two close CME-driven shocks. We find that comparing to the case of a single CME-driven shock, the maximum particle energy, at the second CME-driven shock, can increase significantly due to the enhanced turbulence between the shock pairs. Implications of our calculation to the observations of gradual SEP events are discussed.

1. Introduction

CME-driven shocks are now believed to be responsible for a large portion of solar energetic particle events. As a CME-driven shock propagates out, it is capable of driving a strong turbulence ahead of the shock and accelerate particles to high energies ($\sim$ MeV or even GeV's) as it propagates through the inner heliosphere. The injected particles are either directly from the solar wind or are remnant particles from some other processes such as accompanying solar flares [1]. Understanding the acceleration process, including the injection mechanism, the source population and the subsequent propagation of these energetic particles with the presence of a CME-driven shock is a central topic of heliospheric physics study. It is also of great practice value for space weather study as it will allow one to predict severe space weather conditions that are harmful to both astronauts and electronic equipments onboard spacecraft.

While large SEP events always have CME shocks associated with them, not all fast and strong CME shocks can produce large SEPs. Thus identifying the conditions for a CME-driven shock producing a large SEP event will provide valuable information on how particles are accelerated.

Large SEPs are usually characterized by

1. their infrequency, usually 5 - 10 large events/year in solar-active years.

2. their association with fast CME-driven Shocks (top 1-2%) and/or large flares

3. high energies: particle energies may reach upto GeV's

4. high intensity: intensity >10 pfu ($\mathrm{proton} cm^{-2} s^{-1} sr^{-1}$) at > 10 MeV channel (corresponding to $10^2 \sim 10^6$ increase depending on energy)

5. power law spectrum.

6. composition: electron, proton and heavy ions.

Recently Gopalswamy et al [2] have noticed a possible correlation between large SEP events and intersections

of multiple CMEs. They studied a total of 57 events between 1996-2002, all with intensity > 10pfu at > 10 MeV channels, of which 23 have preceding CMEs (within 1 day) and 20 do not have preceding CMEs. They found that there is a strong correlation between high particle intensity events and the existence of preceding CMEs. They concluded that "higher SEP intensities result whenever a CME is preceded by another wide CME from the same source region and the correlation between the peak intensity and the CME speed is improved substantially over earlier work ([3])." Since not all fast and strong CME shocks are capable of producing large SEPs, the finding of [2] suggests that the occurrence of multiple shocks may provide the necessary conditions for massive particle acceleration at CME-driven shocks. The question of course is how and why multiple shocks are much more efficient to accelerate particles to higher energies with large intensity?

2. Acceleration time scale

In the framework of shock acceleration (also known as first order Fermi acceleration), the acceleration time scale τ_{acc} for accelerating a particle from momentum p_0 to momentum p is [4] and [5],

$$\tau_{acc} = 3s/(s-1) \int_{p_i}^{p_f} \kappa(p)/u_1^2 \delta p/p. \tag{1}$$

Here, $\kappa(p)$ is the particle diffusion coefficient, u_1 the upstream flow speed and s the compression ratio of the shock. If the acceleration time scale $\tau_{acc} \to \infty$, one gets the traditional power law spectrum,

$$f = p^{-3s/(s-1)} \tag{2}$$

In reality the acceleration time scale is finite and energetic particles are subject to loss in the upstream region of the shock [5], thus the spectrum at high energies will deviate from a power law. However, it is clear from equation (1) that to reach higher energies and to obtain higher intensity at high energies, the acceleration time scale τ_{acc} must be small. If indeed that large SEP's are strongly correlated to multiple CME shocks, then it implies τ_{acc} at a multiple-shock environment is much shorter than normal cases of single CME shock.

We now estimate the maximum particle momentum p_f. Assuming particle diffusion coefficient $\kappa(p)$ has the following form,

$$\kappa(p) = p^\alpha = \kappa(p_0)\frac{p}{p_0} = \kappa_0 \frac{p}{p_0} \tag{3}$$

where α is a parameter characterizing the energy dependence of diffusion coefficient ($\alpha = 4/3$ for energetic particles that only experience occasional pitch angle scattering [6]) and p_0 is a reference momentum defined through

$$\frac{3s}{s-1}\frac{\kappa_0}{u_1^2}\frac{1}{\alpha} = \tau_{acc}. \tag{4}$$

Solving equation (1) gives

$$1 = (\frac{p_i}{p_0})^\alpha [(p_f/p_i)^\alpha - 1]. \tag{5}$$

Thus we find

$$p_f \sim \begin{cases} p_0 & \text{if } p_i << p_0 \\ 2^{1/\alpha}p_0 & \text{if } p_f \sim p_0 \\ p_i & \text{if } p_i >> p_0 \end{cases} . \tag{6}$$

Equation (6) is important. It basically states that once the acceleration time scale τ_{acc} (thus p_0) is given, the highest attainable momentum p_f can only be of order p_0 and does not depend on the initial particle momentum

p_i unless the initial particle momentum p_i is larger than p_0. Thus by simply going through two consecutive shocks which have similar τ_{acc}s will not increase a particle's energy dramatically. Therefore, if the presence of two (or multiple) shocks can increase both the maximum particle energy and particle intensity, the acceleration time scale at the second (primary) shock must be shorter. From equation (4), this means the κ_0 at (and near) the second (primary) shock must be smaller than that of the first shock.

3. Turbulence enhancement by preceding CMEs
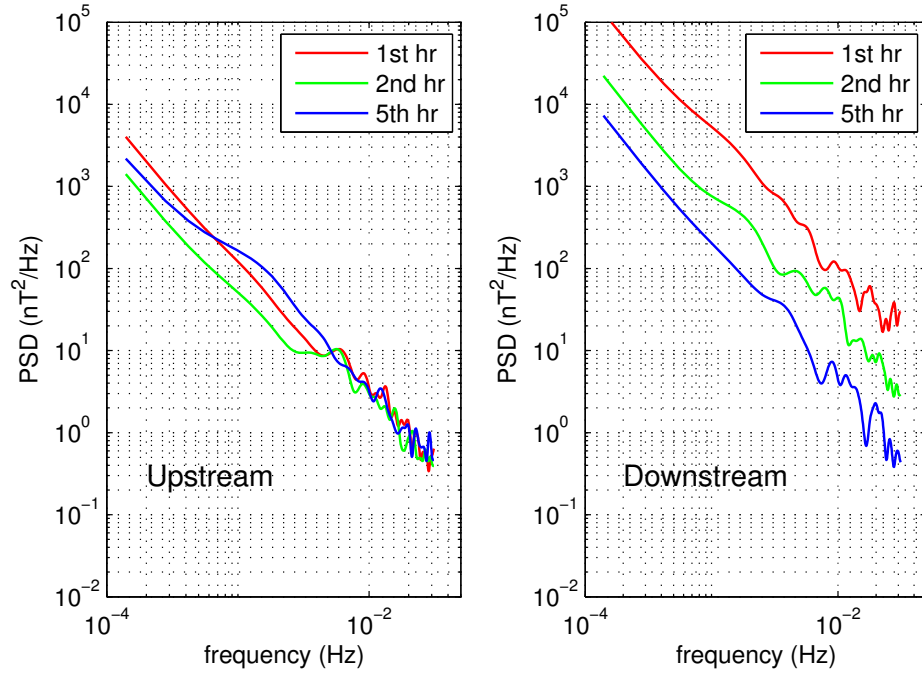
Figure 1. Adapted from [5]. The upstream and down stream wave intensities for the Oct. 29, 2003 event. It is clear that the downstream wave power intensity is much stronger than that of upstream. This observation agrees qualitatively with theoretical work by [8].

In the traditional diffusive shock acceleration picture, particles gain energies by scattering back and forth between the upstream and downstream medium and the scattering is provided by various form of magnetic turbulence. In the case of parallel shock, the upstream and downstream turbulence is believed to be Alfvén waves [7] that are driven by protons streaming away from the shock front. Thus, the maximum particle energy need to be decided self-consistently with the stimulated wave intensity. This picture, however, need to be modified if a preceding shock is followed closely by a primary shock. In this case, the second primary shock will go through a more turbulent medium than the first preceding shock. Since the diffusion coefficient $\kappa(p)$ is proportional to the inverse of wave intensity $1/I(k)$, the second shock becomes a more favorable site for particle acceleration. Furthermore, as shown in Figure 1, upon transmitting the shock front, the wave intensity $I(k)$ usually will be amplified by a factor of $s(s-1) \sim 10$ [8], which further enhances the scattering process upstream the primary shock and allows a quicker particle acceleration. Thus we conclude the presence of

a preceding shock can decrease the acceleration time scale by increasing the turbulence level upstream the primary shock. One can show that a decrease of κ by 10 will lead to an increase of 32 for the maximum particle kinetic energy.

The enhancement of turbulence due to the preceding shock may also decrease the injection energy at the second shock. This is because that, with smaller diffusion coefficient κ, particles are now easier to cross the shock multiple times (a smaller κ makes it easier for particles to "turn around"). Thus, a lower momentum is needed for particles to be injected into the shock front without being outrun. With a lower value of the injection momentum, the number of seed particles will be increased.

4.   Possible observational signatures

If the turbulence upstream the second shock is indeed enhanced by the first shock, one would expect that the observed time intensity profile of energetic particles in large SEP events are different from those of smaller events that are due to single shocks. Thus one way of examining whether the turbulence is strongly enhanced at the primary shock is to study particle spectrograms. We have [9] started examining spectrograms for several large SEP events and some interesting patterns do seem to exist. A further systematic survey on the pre-existing turbulence at CME-driven shocks for large SEP events will be helpful.

5.   Conclusion

There are now evidences that large SEP events usually occur when multiple CMEs occur near the Sun [2]. In this paper, we show that the existence of a preceding CME can greatly enhance the turbulence level upstream the primary shock. This will decrease the particle acceleration time scale; thus increase the maximum particle energy and lead to enhanced particle intensities at high energies. Comparing to a single shock case, an enhancement of turbulence by a factor of ~ 10 due to the transmission of Alfvén wave at the first shock can lead to an increase of maximum energy by a factor of 32. Possible observational signatures via particle spectrograms are discussed.

6.   Acknowledgements

References

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