SHOCK ACCELERATION OF ENERGETIC PARTICLES IN WAVE HEATED CORONA

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ABSTRACT

The solar wind wave heating models require substantial amount of wave power in order to efficiently heat and accelerate solar wind. The level of fluctuations is however limited by energetic particle observations. The simplest cyclotron sweep models result in convection-dominated transport, contradicting observations. However, models incorporating wave-wave -interactions, which cause wave energy to cascade in wavenumber, allow more reasonable energetic particle transport in the interplanetary space. The mean free path of the energetic particles remains still relatively short in the corona, providing favorable conditions for coronal mass ejection (CME) related shock acceleration. We study the consequences of this scenario on the energetic particle production related to CMEs. The role of self-generated waves is also discussed.

INTRODUCTION

Coronal mass ejections (CMEs) are long since believed to be related with energetic particle acceleration near the Sun. Observations suggest that CME driven shocks are capable of accelerating ions to tens of MeV/n as they travel through corona and interplanetary space (Cane et al., 1988). The role of flares and CMEs as accelerators is a subject of continuous discussion.

Although CME accelerated particle modeling has been around for several decades, one crucial observational detail is still missing: the coronal transport properties of the energetic particles, which determine the acceleration efficiency of the shock, are still unknown. The wave power and composition of particle-scattering plasma waves may greatly influence our understanding on the capabilities of shock as particle energizer.

Recently, Vainio and Laitinen (2001) commenced a study relating the requirements of a wave-related solar wind heating model, the cyclotron sweep model (Tu and Marsch, 1997), to energetic particle transport and acceleration. They found that the required wave power exceeded the power allowed by energetic particle observations by several orders of magnitude. However, while the obtained interplanetary transport contradicts observations, the coronal values allow efficient shock acceleration (Laitinen et al., 2002).

The cyclotron sweep model, however, is not consistent with the observed interplanetary plasma turbulence, which suggests that the wave power is cascaded to higher frequencies by nonlinear wave-wave interactions (e.g., Marsch, 1991). The cascading reduces significantly the scattering power, thus allowing a more reasonable interplanetary transport. However, this will also affect the acceleration efficiency of the coronal shock.

In this study we take the first step into incorporating cascading into the coronal acceleration modeling by applying cascade to the wave spectrum required by effective cyclotron heating. We present simulation results of energetic particle acceleration by parallel and oblique shock waves. In addition, we discuss the implications of cascading to the waves generated by the energetic particles themselves, which have been suggested to play an important role in large energetic particle events (Ng and Reames, 1994; Ng et al., 1999).

MODELS

Solar wind

The radial behaviour of the solar wind is obtained from the model of Laitinen et al. (2003), in which the wind is heated by cyclotron resonance at a thermally-dependent dissipation frequency. The model does not take into account the cascading process. Consistent comparison between such a model and energetic particles is, however, beyond the scope of this study. The solar wind model with cascade by Hu et al. (1999) suggests that the lost heating efficiency due to decreased wave power at cyclotron resonance is efficiently supplemented by the spectral flux to the dissipation process. Thus, for the purposes of this study, we will assume that the inclusion of the cascade will not change the characteristics of the solar wind appreciably.

Wave evolution

According to Tu et al. (1984), the wave power P evolves in space and frequency as

$$\frac{v_{\rm A}}{A(u_{\rm sw}+v_{\rm A})}\frac{\partial}{\partial r}\left(\frac{A(u_{\rm sw}+v_{\rm A})}{v_{\rm A}}(u_{\rm sw}+v_{\rm A})P\right)+2\gamma P=-\frac{\partial F}{\partial f}, \tag{1}$$

where γ is the cyclotron resonance dissipation rate, $A \propto B^{-1}$ the cross section of a flux tube with field strength B, and $u_{\rm sw}$ and $v_{\rm A}$ the solar wind and Alfvén velocities, respectively. For the spectral flux function $F(f,r)$ we use the the diffusive description of the wave-wave interaction with Kolmogorov phenomenology, and thus write (Miller and Roberts, 1995)

$$F=-D_{ff}\frac{\partial P}{\partial f}, \quad \text{with} \quad D_{ff}=2\pi C^2\,\frac{v_{\rm A}}{u_{\rm sw}+v_{\rm A}}f^3\sqrt{\frac{fP}{B^2}}, \tag{2}$$

where $C^2=\alpha\alpha_1$ is a cascade constant that determines the cascade strength. In the cascade constant, α_1 is the ratio between inward and outward propagating waves and $\alpha=0.75$ a constant determined from observations, adjusted for the diffusive description (Tu et al., 1989; Vainio, 2002). As α_1 cannot be obtained from the used solar wind model self-consistently, we use an ad-hoc formulation, parametrized with constants c_1 and r_1,

$$\alpha_1=\frac{H(r-r_{\rm A})(r-r_{\rm A})^2+c_1r_1^2}{r_1^2+r^2}, \quad \text{where} \quad H(r)=\begin{cases}0 & r<0\\ 1 & r\geq 0\end{cases} \tag{3}$$

which is separated to a nearly constant low value below the Alfvénic point and an increasing value at larger distances.

Eq. (1) can be solved approximately to give a broken power-law spectrum, which for convenience can be written as

$$P(r,f)=\frac{P_{\rm WKB}(r,f)}{1+[f/f_c(r)]^{2/3}}, \quad \text{with} \quad P_{\rm WKB}(r,f)=P\left(r_\odot,f\right)\frac{B}{B_\odot}\frac{(u_{{\rm sw},\odot}+v_{{\rm A},\odot})^2}{(u_{\rm sw}+v_{\rm A})^2}\frac{v_{\rm A}}{v_{{\rm A}\odot}}, \tag{4}$$

where $P_{\rm WKB}$ is the WKB solution of Eq. (1) with $\gamma=F=0$. In this study we use for the initial spectrum at the sun $P\left(r_\odot,f\right)=P_\odot/f$. The frequency f_c represents the spectral break frequency separating the WKB portion and the inertial range, proportional to $f^{-5/3}$, and can be obtained from

$$\frac{1}{f_c}=3\pi a\frac{P_\odot^{1/2}}{B_\odot}\int_{r_\odot}^{r}{\rm d}r'\,C^2(r')v_{\rm A}(r')\frac{u_{{\rm sw},\odot}+v_{{\rm A},\odot}}{(u_{\rm sw}(r')+v_{\rm A}(r'))^3}\left(\frac{n_{e\odot}}{n_e(r')}\right)^{1/4}, \tag{5}$$

where a is a scaling constant of order unity ($a=1$ in this study) (Vainio, 2002).

Particle transport

Energetic particle transport by parallel Alfvén waves can be modeled by standard quasilinear theory (SQLT) as resonant pitch angle scattering on a resonant wave number, $k_{\rm res}=-\Omega/\mu v$, where Ω, μ and v are the particle's angular gyrofrequency, pitch angle cosine and velocity, respectively (see, e.g., Schlickeiser, 1989). The theory suffers from the well known problem of a resonance gap when parallel velocity vanishes or the wave spectrum has an upper cutoff frequency. We, however, assume that the gap is efficiently closed by phenomena such as turbulence dynamics (Bieber et al., 1994), thermal damping (Schlickeiser and Achatz, 1993), and the effects of dispersion and cross helicity (Vainio, 2000), and apply it for a spectrum with the inertial range continuing to infinite frequencies. The energetic particle mean free path is defined as

$$\lambda=\frac{3v}{8}\int_{-1}^{1}d\mu\frac{\left(1-\mu^2\right)^2}{D_{\mu\mu}}, \quad \text{with} \quad D_{\mu\mu}=\frac{\pi}{2}\Omega(1-\mu^2)\frac{|k_{\rm res}|I(k_{\rm res})}{B^2}, \tag{6}$$

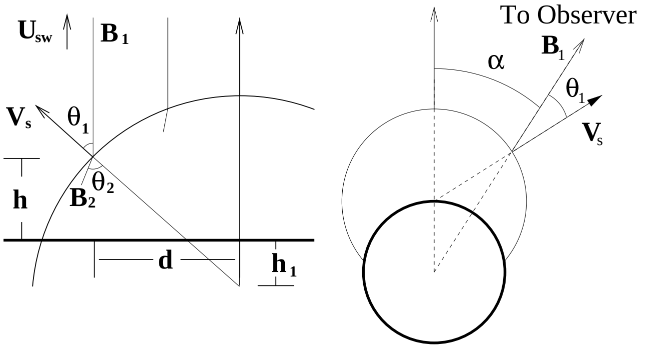

Fig. 1. Spherical shock wave in a “flat Sun” model (left) and “spherical Sun” model (right)

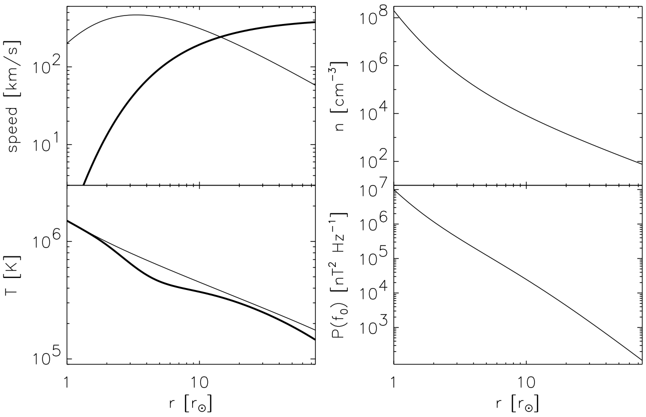

Fig. 2. Slow solar wind profiles. In top left, we show solar wind (thick curve) and Alfvén (thin curve) velocities, and on the right the density. The bottom left panel shows proton (thick curve) and electron (thin curve) temperatures, and the bottom right the evolution of wave power at $f_0 = 1$ Hz.

where $D_{\mu\mu}$ the SQLT pitch angle diffusion coefficient. If we assume no magnetic helicity, the wave number spectrum can be obtained as $|k|\, I(k) = \frac{1}{2} f P(f)$ where $f = (u + v_{\rm A}) \frac{|k|}{2\pi}$. We apply this to the analytic approximation of the cascaded spectrum, Eq. (4), and obtain the mean free path as

$$\lambda = \frac{2}{\pi} \frac{v}{\Omega} \frac{B^2}{f P_{\rm WKB}(r,f)} \left[1 + \frac{27}{7} \left(\frac{\Omega\,(u_{\rm sw} + v_{\rm A})}{2\pi f_c v} \right)^{2/3} \right] \tag{7}$$

CME driven shock

In order to model the evolution of shock obliqueness, we describe the CME as a spherical shock expanding from a “flat Sun” with a constant velocity. Following the shock on a field line at a distance d from the shock axis, results then in a radial behaviour

$$\cos^2\theta_1 \quad = \quad \frac{(r - r_\odot + h_1)^2}{(r - r_\odot + h_1)^2 + d^2}.$$

for the shock angle. Selecting $d = r_\odot \sin\alpha$ and $h_1 = r_\odot(1 - \cos\alpha)$ results in a model with a spherical shock expanding from a spherical Sun, at angular separation α from the observer-connected field line. The models are presented in Figure 1.

The density and magnetic field compression are obtained from the MHD conservation laws and the downstream transport conditions by using the results of Vainio and Schlickeiser (1998). Their results were derived only for parallel shocks and are not fully consistent for this case, as parallel waves will not remain parallel while crossing an oblique shock. For the purposes of this study, however, we find this approximation sufficient.

RESULTS AND DISCUSSION

Efficient particle acceleration by a shock requires super-Alfvénic shock velocities. As we are constrained by the observed velocities for the CMEs, we require a relatively slow solar wind, with low coronal Alfvén velocity. We use the slow solar wind solution of Laitinen et al. (2003), for which the Alfvén velocity doesn’t exceed 700 km/s, and the wind velocity reaches 369 km/s at 0.3 AU. The radial velocity, density, temperature and wave power profiles of the wind model are shown in Figure 2.

The SQLT energetic particle mean free path derived for this wind model, for 10 MeV protons, is shown in Figure 3 with a dashed curve. When the cascade is included, with cascade parameters $c_1 = 0.001$ and $r_1 = 0.1$ AU, the mean free path increases considerably, reaching values 0.04 AU at 1 AU (solid curve).

While the improvement to the WKB model is considerable, the mean free path is still considerably short compared to that suggested by energetic particle observations. There is, however, a known discrepancy between the mean

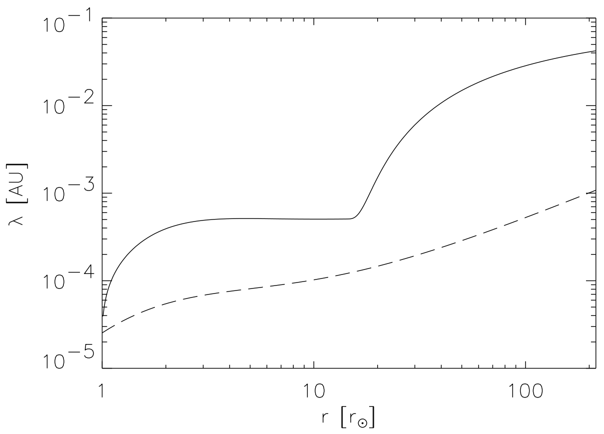

Fig. 3. The mean free path obtained from cascaded spectrum, for 10 MeV protons, using Eq. (7) (solid curve). The WKB portion is shown with dashed curve. The mean free path used in simulations is an order of magnitude longer.

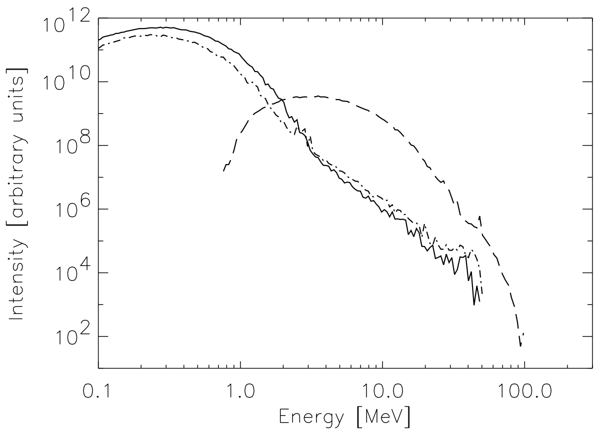

Fig. 4. Time-integrated spectra from shock injection to arrival to 0.2 AU, for parallel shock (solid curve), $\alpha = 60°$ model (dash-dotted curve), and "flat Sun" shock with $d = 4r_\odot$ and $h_1 = 0.4r_\odot$ (dashed curve). The non-accelerated spectrum has been subtracted.

free paths derived from energetic particle observations and those derived from solar wind observations, where the difference can be even an order of magnitude. While the matter has been studied intensively, (e.g., Bieber et al., 1994), consistent treatment of the problem is beyond the scope of this study. Here we correct for the discrepancy by increasing the mean free path obtained from the solar wind model by an order of magnitude in the simulations.

We have conducted Monte Carlo test particle acceleration and transport simulations (see, e.g., Vainio et al., 2000) for energetic protons using the presented solar wind, cascade and CME models. The shock speed is taken to be 1000 km/s. The particles are injected to the acceleration and transport process as a beam from the solar surface, with spectrum $\propto p^{-5}$, from 50 keV to 50 MeV, simultaneously with the shock launch on the local field line. The particles are observed at the distance of 0.2 AU, until the shock reaches the observer. The shock obliqueness is taken into account by assuming that the particle's magnetic moment is conserved.

In Figure 4 we show the time-integrated spectra for three different shock profiles. The spectrum resulting from mere transport of the injected particles has been subtracted from the spectra. The solid curve represents the spectrum of acceleration by a parallel shock ($\theta = 0$, i.e. $d = 0$ in the "flat Sun" model). The low-energy particles are accelerated until they reach ~ 0.5 MeV. After this, the acceleration efficiency decreases, as the particles focus adiabatically to the upstream, away from the shock. The spectrum steepens, until, at ~ 3 MeV, major portion of the spectrum is formed from original solar injection (subtracted from the curve). These particles typically interact with the shock once, and produce a power law spectrum $\propto E^{-3}$. This process resembles shock drift acceleration.

We next used the "spherical Sun" model to simulate particles accelerated by an earth-directed spherical CME, as they would be observed on an earth-connected spiral field line, with the angular separation of $\alpha = 60°$ from the CME axis. The spectrum in this case is shown in Figure 4 by a dash-dotted curve. The spectral level at the maximum is now slightly lower, as the low-energy particles are lost more efficiently to downstream. However, the energy gained during each shock crossing is also higher, and thus the spectrum is slightly harder.

The difference to the parallel shock, however, is very small, and the desired > 10 MeV energies can not be reached. In order to reach those energies, we turned to the "flat Sun" model, where, by adjusting the parameters d and h_1, we can obtain profiles which remain very oblique for larger heights. Choosing $d = 4\ r_\odot$ and $h_1 = 0.4\ r_\odot$, we obtain a profile which has shock angle of $\sim 85°$ at the solar surface, and $45°$ still at $3.6\ r_\odot$. With such model we can successfully accelerate particles up to 10 MeV, before the particles begin to escape the acceleration process. In addition, a spectrum with power law index rolling from -5 to -6 up to 100 MeV, excluding the step caused by the particles accelerated from the injection spectrum tail at ~ 50 MeV, has been obtained. Obtaining particles with energies lower than 1 MeV requires continuous thermal injection, which is not included in the simulations.

In high-intensity particle events, the energetic particle beams are capable of generating waves through streaming instability. Such waves may decrease significantly the mean free path of the energetic particles in the upstream of the shock, trapping the particles more efficiently to the acceleration process. While this effect and its consequences to the acceleration scenario have been studied numerically (e.g., Ng et al., 1999), the nonlinear interactions between the waves have not been sufficiently addressed.

We present a simple estimation for this effect by comparing the wave generation rate and the cascade process, setting

$$\left|\frac{\partial F}{\partial f}\right|_{f_r} \sim |2\gamma_{\max} P|_{f_r} \tag{8}$$

Assuming that the resonant frequency is in the inertial part of the spectrum, where $P \approx P_{\rm WKB}\,[f_c/f]^{2/3}$, using Eq. (1) we find, that

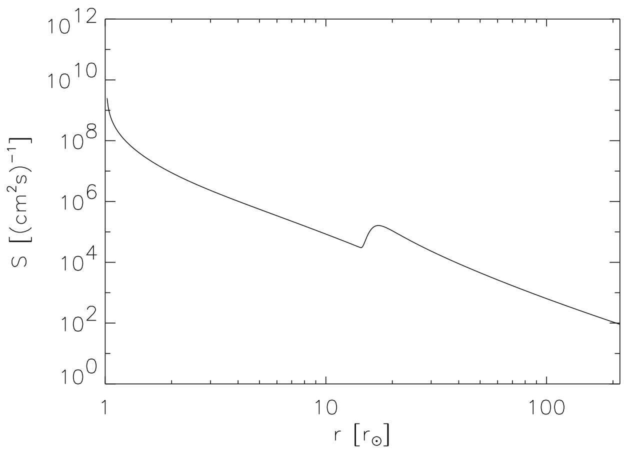

Fig. 5. The minimum required streaming S which allows the generated waves to overcome the cascade process.

$$\left|\frac{\partial F}{\partial f}\right|_{f_r} \approx (u_{\rm sw}+v_{\rm A})P_{\rm WKB}\frac{2}{3f_c}\left(\frac{f_c}{f_r}\right)^{2/3}\left|\frac{\partial f_c}{\partial r}\right| \sim 2\gamma_{\max}P_{\rm WKB}\left(\frac{f_c}{f_r}\right)^{2/3}. \tag{9}$$

The wave amplification coefficient for self-generated waves is $\gamma_s = \Omega_p \frac{\pi S}{4 n_e v_{\rm A}}$ (Vainio and Kocharov, 2001), where the streaming is given by $S \approx 8\pi\langle\mu\rangle E I$, with $\langle\mu\rangle$ average pitch angle, E the particle's energy and I differential intensity. Thus we find that if

$$S < \frac{4 n_e v_{\rm A}(u_{\rm sw}+v_{\rm A})}{3\pi\Omega_p f_c}\left|\frac{\partial f_c}{\partial r}\right|, \tag{10}$$

the cascade overcomes the wave generation and the effects of the self-generated waves can be neglected. We show this limit in Figure 5, for cascade scenario with $c_1 = 0.001$ and $r_1 = 0.1$ AU in Eq. (3). The values at 1 AU are consistent with the so-called streaming limited intensities (Reames and Ng, 1998).

As can be seen, only events with strong streaming are capable of generating waves through streaming instability. In such events, the proposed cascade model favours wave generation below Alfvénic point, where the cascade is not yet efficient, and particles are trapped to the acceleration process. Above the Alfvénic point, where the cascade dissipates the generated waves efficiently, the particles are rapidly released, causing a delayed injection of energetic particles into interplanetary space. Our test particle approach is suitable for small gradual events with proton streaming well below the wave generation threshold.

Thus, we find that while the cascade decreases the shock acceleration efficiency, as compared to results of Laitinen et al. (2002), we still can achieve > 10 MeV energies for protons, if the shock remains oblique for sufficiently long time. The simple assumption of a spherical shock expanding from the spherical Sun was found ineffective, but a model with $> 45°$ obliqueness up to $\sim 4\ r_\odot$ is already sufficient. Such shock geometries may result as non-spherical CMEs travel through the complex, non-radial coronal magnetic fields.

The treatment presented in this paper, however, is not fully consistent, as the effect of the cascade was not incorporated to the solar wind modeling. Thus we do not know, if a slow and dense enough solar wind could be obtained to ensure efficient shock acceleration with the proposed cascade scenario. In order to obtain quantitative results, we must conduct the modeling of the solar wind and energetic particles in parallel, using continuously the results of one as constraints of the other.

CONCLUSIONS

We have modeled the coronal energetic particle acceleration in an environment derived from solar wind heating modeling. While the used solar wind model lacks wave-wave -interactions, we incorporated these effects to the required wave profile, as a first step into modeling coronal energetic particle acceleration in a cascaded wind. We find that, while a parallel shock fails to accelerate particles to high energies, an oblique shock is able to accelerate particles efficiently to > 10 MeV energies in the corona.

We also studied the implications of the cascade to wave generation by the energetic particle anisotropies, which has been suggested to play an important role in shock acceleration processes. We find that the cascade dominates over wave generation for smaller events. For large events, the particles are accelerated efficiently below Alfvénic point, where the cascade in the proposed model is weak, and subsequently rapidly released, as the cascade dissipates the generated waves in the super-Alfvénic solar wind.

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Manuscript received 29 Nov 2002; revised 17 Jan 2003; accepted 22 Jan 2003