29th International Cosmic Ray Conference Pune (2005) **1**, 125–128

SEP Acceleration at Realistic CMEs: Two Sites of Acceleration?

J. Kóta[a], W.B. Manchester[b] and T.I. Gombosi[b]

(a) The University of Arizona, Lunar and Planetary Laboratory, Tucson AZ 85721-0092, USA

(b) The University of Michigan, Center for Space Environment Modeling, Ann Arbor, MI 48109-2143 , USA

Presenter: J. Kóta (kota@lpl.arizona.edu), usa-kota-J-abs3-sh13-poster

We combine the SEP acceleration and transport code of Arizona with realistic CME simulations from Michigan. We suggest that, in addition to the shock, there is another important site of acceleration: significant particle acceleration can occur in the sheath behind the shock, where magnetic field lines are compressed. Our SEP code considers field-aligned motion of ions, undergoing pitch-angle scattering. We cast the Fokker-Planck equation into a new form, which is suitable to follow the evolution of the magnetic field as the CME expands. Illustrative simulation results are presented.

1. Introduction

Large gradual solar energetic particle (SEP) events are thought to be accelerated by CME driven shocks, but the precise mechanism of acceleration is not yet fully understood. In shock acceleration, the shock geometry plays a central role. Many of the current theoretical models presume a parallel shock as the site of acceleration. On the other hand, Jokipii [1] pointed out that acceleration can be significantly faster at quasi-perpendicular shocks. Recently Giacalone [2] proposed that efficient SEP acceleration may occur at perpendicular rather than parallel shocks. Lee and Tylka [3] emphasize that the the shock is likely to change from an initially perpendicular shock to a more parallel one later as the CME expands.

Current models of CME propagation into interplanetary space [4] [5] indicate that the downstream region immediately beyond the shock has a remarkable structure of it own. We suggest that the models with a single parallel shock may be insufficient: there are more than one site of acceleration to be considered. Field lines pushed by the expanding CME are bent and strongly compressed between the CME and the shock. Acceleration due to this strengthening of the magnetic field effects both the injection and acceleration processes [6].

2. Structure of a CME

The structure of the sheath formed by the shocked solar wind between the shock and the magnetic cloud of the CME is discussed in detail in [5]. Figure 1 shows one selected field line from the 3-D MHD simulation of [4] that connects almost head-on to the CME. The plasma is pushed upward in latitude with little longitudinal deflection. While the shock is nearly parallel, the magnetic field strengthens abruptly in the sheath behind the shock where field lines are strongly compressed as they bend around the expanding CME.

In this scenario, we find at least two important sites of SEP acceleration. The upper right box of Fig. 1 reveals a finer structure. First there is a nearly parallel shock, where the density, n jumps but the magnetic field, B does not. Second, due to the bending and compression in the sheath, there is a sharp increase of the magnetic field close, but distinctly behind the shock. Particles can be accelerated at both sites. We recall that acceleration can occur even without net compression: particles reflected from the stronger field gain energy. For particles of large-pitch angle, the compression in the sheath acts much like a quasi-perpendicular shock.

To underscore the importance of this compression of the field lines, below we present a simple Monte-Carlo simulation. Consider a simple 1-D model as shown in the right panel of Fig. 1 which resembles the CME

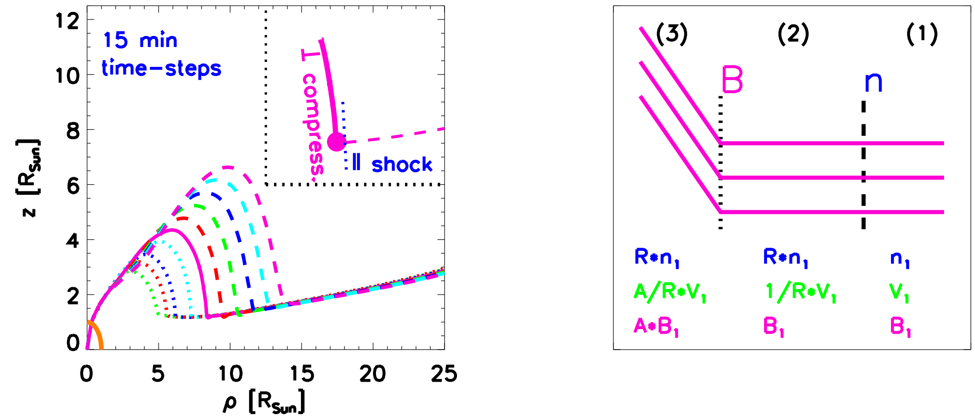

Figure 1. Time-evolution of one selected field line from [4]. Lines depict the meridional projection of the selected field line in 15 minute consecutive time steps. The box (upper right) shows a schematic illustration around the shock, the circle marking the location where the field strengthens due to the compression in the sheath formed between the shock and the magnetic cloud. The right panel shows the simple idealized structure of our MC simulation (see text)

structure. The the plasma flowing from right to left undergoes first a transition at a parallel shock (dashed line) where the density, n, jumps from n_1 to $n_2 = R\,n_1$, but the magnetic field, B, remains the same ($B_2 = B_1$), then suffers a deflection (dotted line) where B increases ($B_3 = A\,B_1$). We follow 10,000 test particles moving along field lines and undergoing pitch-angle scattering. Figure 2 shows the resulting spectra from all particles after $t = 1000\lambda_{||}/V_1$ for $R = 4$, $A = 3$. Inspection of Fig. 2 shows that the composite structure with defection behind a parallel shock (right panel) is more efficient and than the parallel shock alone (left panel).

3. Illustrative Simulation Results

Our purpose is to couple the Arizona SEP acceleration/transport code with 3-D CME simulations obtained by the BATS-R-US code at Michigan [4], [5]. To follow the constantly changing structure of the shock and the magnetic field around the CME, we cast the field-aligned transport-equation [7] [8], [9] into the frame, co-moving with the solar wind plasma (for details see [6]) which results in:

$$\Big(1-\frac{(V_i b_i) w\mu)}{c^2}\Big)\frac{Df}{Dt}+w\,\mu\frac{\partial f}{\partial s}+\frac{(1-\mu^2)}{2}\left[\frac{w}{L}-\frac{2}{w}b_i\,\frac{DV_i}{Dt}+\mu\frac{D\,ln(n^2/B^3)}{Dt}\right]\frac{\partial f}{\partial\mu}+$$

$$+\left[-\frac{\mu b_i}{w}\,\frac{DV_i}{Dt}+\mu^2\frac{D\,ln(n/B)}{Dt}+\frac{(1-\mu^2)}{2}\frac{D\,ln\,B}{Dt}\right]\frac{\partial f}{\partial ln\,p}=\frac{\partial}{\partial\mu}\Big(\frac{D_{\mu\mu}}{2}\frac{\partial f}{\partial\mu}\Big)+q \qquad (1)$$

The notation, D/Dt stands for Lagrangian derivatives, i.e. $D/Dt = \partial/\partial t + V_j\partial/\partial x_j$. Convection, in this description, is absorbed into the first term of the LHS. The unit vector, $b_i = B_i/B$ points along the magnetic field, B_i. The right hand side accounts for random pitch-angle scattering, and for sources of particle injection.

An important implication of Eq. (1) is that acceleration is divided into two major terms: acceleration due to

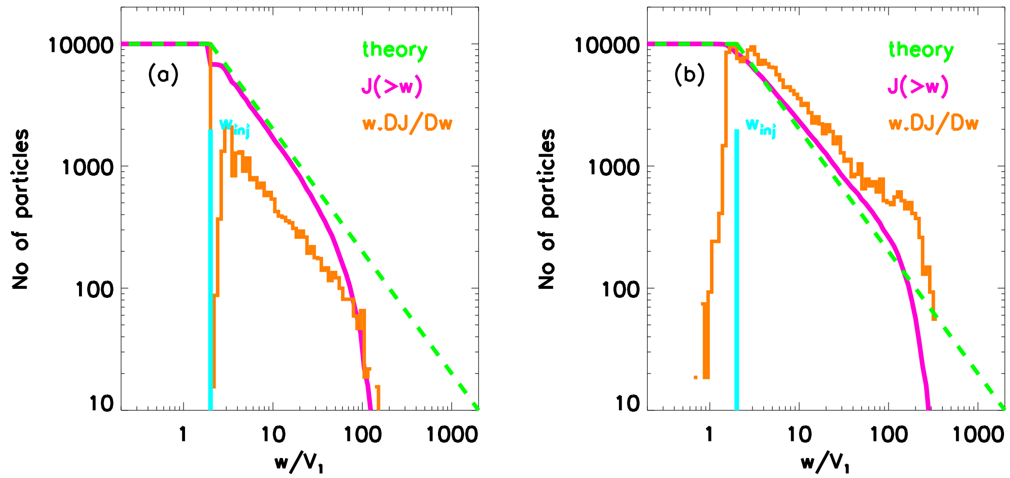

Figure 2. Comparison of acceleration efficiency for a parallel shock only (a) and that with a deflection behind the shock (b). Dashed lines indicate predictions of standard diffusion theory

compressions parallel and perpendicular to the field, respectively. Parallel shocks, which have parallel compression only, accelerate particles moving along the field more efficiently, and require many scatterings to accelerate. Compressions perpendicular to the field, which occur at quasi-perpendicular shocks, are accompanied by corresponding increases in B and may accelerate charged particles faster [1].

At present, we treat scattering phenomenologically and assume a pitch-angle scattering coefficient, $D_{\mu\mu}$, which is enhanced in the shock to account for self-generated waves [10], [11], [12]. We prescribe an enhancement of 100 which decreases upstream exponentially on a scale of $0.1r_{sh}$. In this work, we take a simple approach and use similarity solutions as a plausible way for describing the evolution of the field and plasma around the CME. Fig. 1 suggests that the CME evolves in quite self similar way. We adopted the simulation of [4] at a time when the shock has already formed and extend it as a similarity solution for later times. Figure 3 shows the time profiles at 1 AU as obtained for five different energies in one simulation for a single field line. These profiles are no longer applicable for observations at Earth after the passage of the shock, as the Earth moves onto a new field line of a very different environment. Also shown in Fig. 3 (right panel) are the time profiles obtained at the moving shock. We find that acceleration is quite fast. Few MeV fluxes reach maximum level almost instantly, while it takes about 10-20 minutes to reach maximum flux at ∼500 MeV.

4. Conclusions

The constantly changing geometry of the shock and magnetic field lines around the CME calls for a computational scheme that follows the evolving field lines as te CME expands. We have developed a numerical code that suits this task. The code employs grid-points co-moving with fluid elements. For this purpose first we rewrite the standard field field-aligned transport equation [7] [8] [9]. An additional benefit of the new from of the Eq. (1) is that all transport coefficients (e.g. acceleration rates) are expressed in terms of the temporal variation of the plasma velocity, V_i, density, n, and magnetic field strength, B, at a given fluid element. There is no need to compute spatial derivatives of the solar wind speed, V_i.

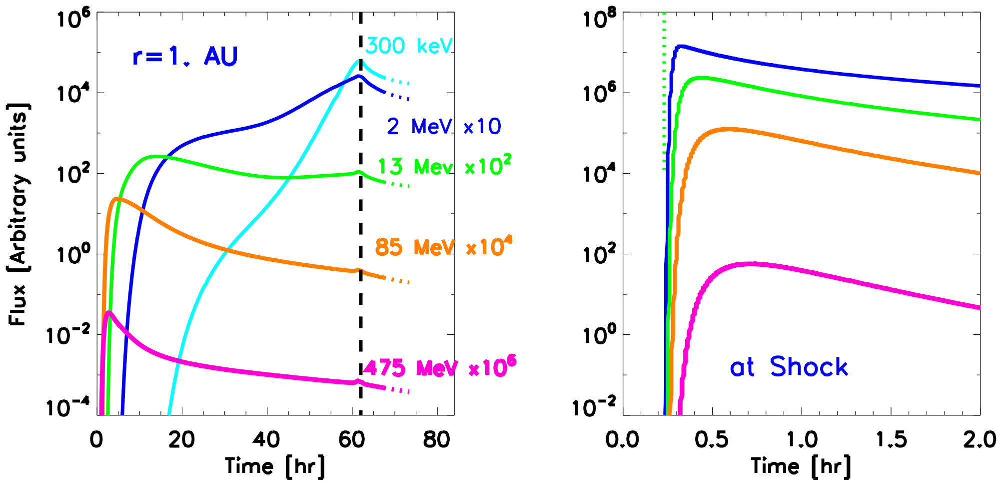

Figure 3. Time-profiles obtained for 0.3, 2, 13, 85 and 475 MeV proton fluxes at 1 AU in a a simulated SEP event. The vertical dashed line marks the arrival of the CME-driven shock at Earth, after which the simulations is no longer applicable. The right panel shows shock time-profiles at the moving shock.

The SEP code, which considers field aligned motion of ions, is designed to couple our particle acceleration and transport model with realistic CME simulations. We find that models with a single shock may be insufficient. The strengthening of the magnetic field in the sheath may result in significant additional acceleration which cannot be readily accounted for in simple diffusion models.

5. Acknowledgements

The authors benefited from discussions with J.R. Jokipii and J. Giacalone, This work has been supported by NASA ESS Cooperative agreement NCC5-614, and by DoD MURI grant F49620-01-1-0359.

References

[1] J.R. Jokipii, Astrophys. J., 313, 842 (1987)
[2] J. Giacalone, Astrophys. J., 624, 765, (2005)
[3] M.A. Lee and A.J. Tylka, to be published (2005)
[4] W.B. Manchester, et al., J. Geophys. Res., 109, 1102, (2004)
[5] W.B. Manchester, IV et al., Astrophys. J., 662, 1225, (2005)
[6] J. Kóta et al., Astrophys. J., submitted (2005).
[7] J. Skilling, Astrophys. J., 170, 265 (1971).
[8] D. Ruffolo, Astrophys. J., 442, 861 (1995)
[9] P.A. Isenberg, J. Geophys. Res., 102, 4719 (1997)
[10] M.A. Lee, J. Geophys. Res., 88, 6109 (1983)
[11] C.K. Ng and D.V. Reames, and A.J. Tylka, Astrophys. J., 591, 461, (2003)
[12] G.P. Zank, et al., J. Geophys. Res., 105, 25 079 (2000).