บรรณานุกรม

Bell, A.R. 1978. The acceleration of cosmic rays in shock fronts--I. Monthly Notices of Royal Astronomical Society 182: 147-156.

Channok, C., Ruffolo, D., Desai, M.I. and Mason, G.M. 2005. Finite time shock acceleration of energetic storm particles Astrophysical Journal 633, L53-L56.

Desai, M.I., Mason, G.M., Dwyer, J.R., Mazur, J.E., Gold, R.E., Krimigis, S.M., Smith, C.W. and Skoug, R.M. 2003. Evidence for a suprathermal seed population of heavy ions accelerated by interplanetary shocks near 1 AU. Astrophysical Journal 588: 1149-1162.

Desai, M.I. Mason, G.M. Wiedenbeck, M.E., Cohen, C.M., Mazur, J.E., Dwyer, J.R, Gold, R.E., Krimigis, S.M., Hu, Q., Smith, C.W. and Skoug, R.M. 2004. Spectral properties of heavy ions associated with the passage of interplanetary shocks at 1 AU. Astrophysical Journal 611: 1156-1174.

Drury, L. 1983. An introduction to the theory of diffusive shock acceleration of energetic particles in tenuous plasmas. Reports on Progress in Physics 46: 973-1027.

Fermi, E. 1954. Galactic magnetic fields and the origin of cosmic ray radiation. Astrophysical Journal 119: 1-6.

Forman, M.A. 1981.Acceleration theory for 5-40 keV ions at interplanetary shock. Advances in Space Research 1: 97-100.

Kallenrode, M. 2001. Space Physics. Heidelberg: Springle-Verlag

Krymskii, G.F. 1977. A regular mechanism for the acceleration of changed particles on the front of a shock wave. Soviet Physics Doklady 22: 327-328.

Lang, K.M. 2001. The Cambridge encyclopedia of the Sun. Cambridge: Cambridge Press.

Manchester, W.B., Gombosi, T.I., De Zeeuw, D.L., Sokolov, I.V., Roussev, I.I., Powell, K.G., Kóta, J., Tóth, G. and Zurbuchen, T.H. 2005. Coronal mass ejection shock and sheath structures relevant to particle acceleration. Astrophysical Journal 622: 1225-1239.

Mason, G.M., Gold, R.E., Krimigis, S.M., Mazur, J.E., Andrews, G.B., Daley, K.A., Dwyer, J.R., Heuerman, K.F., James, T.L., Kennedy, M.J., Lefevere, T., Malcolm, H., Tossman, B. and Walpole, P.H. 1998, The Ultra Low Energy Isotope Spectrometer (ULEIS) for the ACE spacecraft. Space Science Review 86: 409-448.

Ng, C.K., Reames, D.V. and Tylka, A.J. 1999, Effect of proton-amplified waves on the evolution of solar energetic particle composition in gradual events. Geophysical Research Letters 26: 2145-2148.

Palmer, I.D. 1982. Transport coefficient of low-energy cosmic rays in interplanetary space. Reviews of Geophysics and Space Physics 20: 335-351.

Tylka, A.J. 2001. New insights on solar energetic particles from Wind and ACE. Journal of Geophysical Research 106: 25333-25352.

ภาคผนวก

ผลงานตีพิมพ์ในวารสารวิชาการจากโครงการวิจัย

- Chanruangrit Channok & David Ruffolo. *Spatial Profile of Solar Storm Particle during Finite-Time Shock Accelaration*. The 12th Annual Symposium on Computational Science and Enginering (2008) pp173-176.

Spatial Profiles of Solar Storm Particles during Finite-Time Shock Acceleration

Chanraungrit Channok,[1,C] **and David Ruffolo**[2]
[1]*Department of Physics, Faculty of Science, Ubonrajathani University, Ubonrajathani 34190, Thailand*
[2] *Department of Physics, Faculty of Science, Mahidol University, Bangkok 10400, Thailand*
[C]**E-mail**: physics007@yahoo.com; **Fax**: 66-45-288381; **Tel**: 66-45-288381

ABSTRACT

We apply a model of finite time shock acceleration for energetic storm particle events at interplanetary shocks to describe the spatial profiles of energetic ions during events in September 1999 and October 2000. The finite time shock acceleration model is a development of the diffusive shock acceleration mechanism, incorporating rigidity-dependent scattering due to magnetic turbulence in astrophysical shock phenomena. A system of coupled ordinary differential equations is solved to describe the time evolution of the particle density at tens or hundreds of energy values. A simultaneous fit to the spectra of carbon, oxygen, and iron ions is used to determine a key parameter, the scattering mean free path λ, as a function of particle rigidity. Next, we model the spatial profiles by solving the parabolic partial differential equation for particle diffusion, either analytically (for a steady state) or numerically (for time evolution). We aim to compare the results with measured spatial profiles of solar storm particles from Ultra-Low-Energy Isotope Spectrometer (ULEIS) on board the Advanced Composition Explorer (ACE) spacecraft.

Keywords: Shock acceleration, interplanetary shock, energetic storm particle event

INTRODUCTION

The Earth is impacted by energetic particles from the Sun and Galactic cosmic rays, including particles from various sources in our galaxy. The most energetic particles in the solar system are released from the Sun. The energetic particles from the Sun consist of protons, electrons and heavy ions with energy ranging from a few tens of keV to GeV (the fastest particles can reach speed up to 80% of the speed of light). They are of particular interest and importance because they can endanger life in outer space (especially particles above 40 MeV). Solar energetic particles (SEPs) can originate from two processes: energetization at a solar flare site or by shock waves associated with coronal mass ejection (CMEs).

Particle acceleration occurs as a consequence of transient releases of energy in association with solar flares or coronal mass ejections. When a shock wave develops, it expands and propagates through the interplanetary medium. If the magnetohydrodynamic strength of the shock is high enough, it is able to accelerate particles which propagate along the interplanetary magnetic field (IMF) lines (see figure 1).

The observed spectra of energetic particles from the Sun can indicate enhanced intensity in association with the passage of interplanetary shocks. These are known as solar storm particles or energetic storm particles (ESP) [1]. These typically exhibit spectral rollovers at 0.1 to 10 MeV nucleon^{-1} [2,3]. The physical origin of such rollovers is the finite time available for shock acceleration.

We apply a model of finite time shock acceleration for energetic storm particle events at interplanetary shocks to describe the spatial profiles of energetic ions during events in solar cycle 23 (during September 1999 and October 2000). The finite time shock acceleration model is a development of the diffusive shock acceleration mechanism, incorporating rigidity-dependent scattering due to magnetic turbulence in astrophysical shock phenomena [4]. A system of coupled ordinary differential equations is solved to describe the time evolution of the particle density at tens or hundreds of energy values. A simultaneous fit to the spectra of carbon, oxygen, and iron ions is used to determine a key parameter, the scattering mean free path *(λ)*, as a function of particle rigidity.

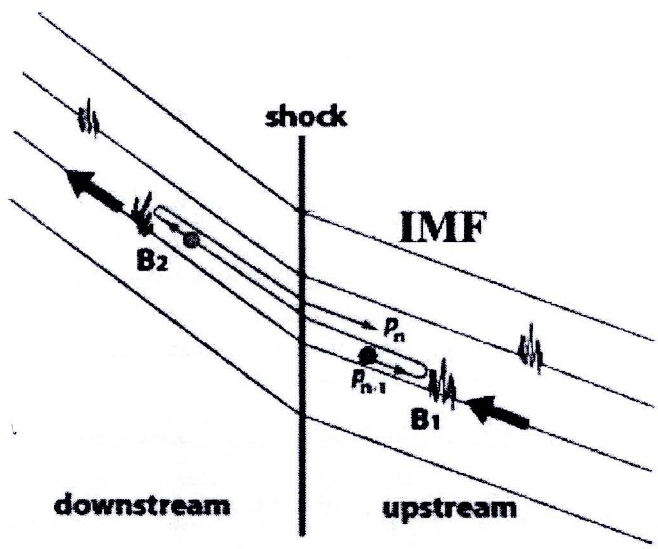

Figure 1. Acceleration of a particle propagating along the interplanetary magnetic field (IMF) lines crossing the shock (discontinuity of direction of magnetic field, ***B***).

COMPUTATIONAL METHOD

The finite-time shock acceleration (FTSA) model [5] is based on the probabilistic model. The key quantities are the number of acceleration events, *n*, the rate of acceleration events, *r*, the rate of escape ε, and the duration of the shock acceleration process, *t*. The mathematical model of the finite-time shock acceleration is a system of coupled ordinary differential equations, which is solved to describe the time evolution of the particle density, *N(t)*:

$$\frac{dN_n(t)}{dt} = I_n - (r_n + \varepsilon_n)N_n(t) + r_{n-1}N_{n-1}(t) \qquad (1)$$

where $N_n(t)$ is the particle density, r_n is the rate of acceleration, ε_n is the rate of escape, and I_n is the rate of particle inflow to the shock (the subscript *n* is the number of acceleration events).

We model the spatial profiles by solving the parabolic partial differential equation for particle diffusion, either analytically (for a steady state) or numerically (for time evolution). Consider the diffusion convection equation (equation 2) for describing the particle density, *F* at the shock of interplanetary space ($z = 0$).

$$\frac{\partial F}{\partial t} = \kappa \frac{\partial^2 F}{\partial z^2} - U \frac{\partial F}{\partial z} \qquad (2)$$

where $F(z,t)$ is the particle density at position *z* at time *t*, U is the fluid speed, and κ is the spatial diffusion coefficient.

We set a boundary condition at the shock of $F(z=0) = N_0 \exp(t/\tau)$ and at positions far from the shock of $F(z \to \infty) = F(z \to -\infty) = N_0$, where N_0 is the seed particle density and τ is the exponential time scale. For the initial condition we set $F(z, t=0) = N_0$.

We solve equation (2) with finite differencing by the Crank-Nicolson Method. We write it in discrete form as

$$\frac{F_i^{n+1} - F_i^n}{\Delta t} = \kappa \frac{1}{\Delta z^2}\left[\frac{(F_{i+1}^{n+1} - 2F_i^{n+1} + F_{i-1}^{n+1}) + (F_{i+1}^n - 2F_i^n + F_{i-1}^n)}{2}\right] - U\frac{1}{\Delta z}\left[\frac{(F_{i+1}^{n+1} - F_{i-1}^{n+1}) + (F_{i+1}^n - F_{i-1}^n)}{4}\right]. \quad (3)$$

Then

$$F_i^{n+1} = F_i^n + \kappa \frac{\Delta t}{\Delta z^2}\left[\frac{(F_{i+1}^{n+1} - 2F_i^{n+1} + F_{i-1}^{n+1}) + (F_{i+1}^n - 2F_i^n + F_{i-1}^n)}{2}\right] - U\frac{\Delta t}{\Delta z}\left[\frac{(F_{i+1}^{n+1} - F_{i-1}^{n+1}) + (F_{i+1}^n - F_{i-1}^n)}{4}\right] \quad (4)$$

and we get

$$F_i^{n+1} = F_i^n + A\left[(F_{i+1}^{n+1} - 2F_i^{n+1} + F_{i-1}^{n+1}) + (F_{i+1}^n - 2F_i^n + F_{i-1}^n)\right] - B\left[(F_{i+1}^{n+1} - F_{i-1}^{n+1}) + (F_{i+1}^n - F_{i-1}^n)\right] \quad (5)$$

where $A = \kappa \dfrac{\Delta t}{2\Delta z^2}$ and $B = U\dfrac{\Delta t}{4\Delta z}$.

RESULTS AND DISCUSSION

We show the numerical results of the particle density at the interplanetary shock *(z=0.5 AU)* at different times for a solar storm particle event (October 2000) in figure 2.

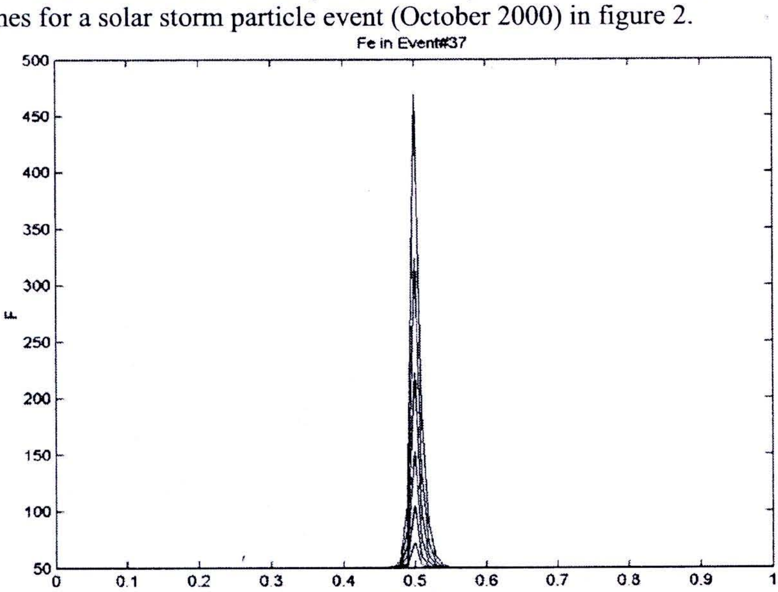

Figure 2. Results from numerical calculation at the shock at different times for Fe ions for the October 2000 event.Figure description.

We compare the results with measured spatial profiles of solar storm particles from the Ultra-Low-Energy Isotope Spectrometer (ULEIS) on board the Advanced Composition Explorer

(ACE) spacecraft. Our model previously provided a good fit to spectra of C, O, and Fe ions observed by ACE/ULEIS near the shock for 2 energetic storm particle (ESP) events in September 1999 and October 2000 [2].

LITERATURE CITED

1. Bryant, D., Cline, T., Desai, U. and McDonald, F. J. Geophys. Res. 1962, 67, 4953-4960
2. Desai, M. et al., Astrophys. J. 2004, 611, 1156-1165
3. Gosling, J. et al., J. Geophys. Res. 1981, 86, 547-554.
4. Fermi, E. Astrophys. J. 1954, 199, 1-9.
5. Channok, C., Ruffolo, D., Desai, M., and Mason, G., Astrophys. J., 2005, 633, L53-L56

ACKNOWLEDGMENTS

This work was supported by the Thailand Research Fund.