Table 2: Comparison between numerical and theoretical results of the diffusion coefficients for 20% slab and 80% two-dimensional energies when ξ is varied.

Run	ξ	D_x theory	D_y theory	D_x sim.	D_y sim.	ΔD_x (%)	ΔD_y (%)	$\kappa^x = \frac{\langle \Delta x^4 \rangle}{\langle \Delta x^2 \rangle^2}$	$\kappa^y = \frac{\langle \Delta y^4 \rangle}{\langle \Delta y^2 \rangle^2}$
1	0.25	0.0550	0.4038	0.0556	0.3767	+1.15	-6.72	2.90	3.05
2	1/3	0.0711	0.3748	0.0722	0.3449	+1.60	-7.98	3.00	3.01
3	0.5	0.1053	0.3172	0.1016	0.2771	-3.50	-12.64	3.01	2.95
4	2/3	0.1392	0.2692	0.1340	0.2386	-3.77	-11.36	3.15	3.05
5	1.0	0.2000	0.2000	0.1812	0.1778	-9.43	-11.10	3.09	2.97
6	1.5	0.2692	0.1392	0.2350	0.1310	-12.70	-5.88	3.04	3.01
7	2.0	0.3172	0.1053	0.2897	0.1021	-8.68	-3.02	2.98	2.93
8	3.0	0.3748	0.0711	0.3535	0.0699	-5.68	-1.73	3.02	2.95
9	4.0	0.4038	0.0550	0.3758	0.0572	-6.94	+4.07	3.02	2.89

Table 3: Comparison between numerical and theoretical results of the diffusion coefficients for 80% slab and 20% two-dimensional energies when ξ is varied.

Run	ξ	D_x theory	D_y theory	D_x sim.	D_y sim.	ΔD_x (%)	ΔD_y (%)
1	0.25	0.0923	0.1508	0.0894	0.1651	-3.20	+9.44
2	1/3	0.0991	0.1574	0.0984	0.1653	-0.69	+5.06
3	0.5	0.1122	0.1595	0.1155	0.1688	+2.91	+5.84
4	2/3	0.1241	0.1554	0.1283	0.1636	+3.38	+5.27
5	1.0	0.1418	0.1418	0.1439	0.1448	+1.51	+2.16
6	1.5	0.1554	0.1241	0.1640	0.1275	+5.58	+2.72
7	2.0	0.1597	0.1123	0.1653	0.1119	+3.49	-0.41
8	3.0	0.1574	0.0991	0.1700	0.0981	+8.02	-0.93
9	4.0	0.1508	0.0923	0.1622	0.0904	+7.51	-2.09

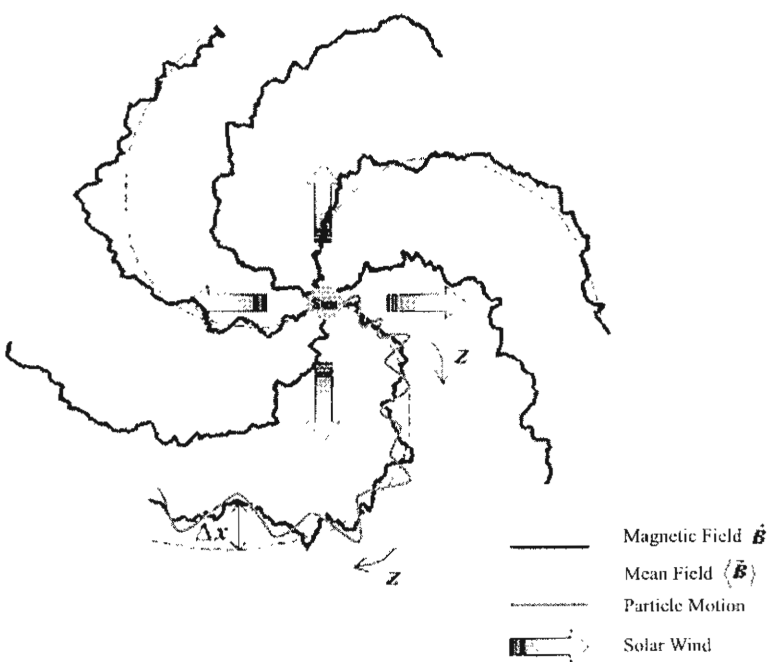
Table 4: Comparison between numerical and theoretical results of the diffusion coefficients when we vary all non-axisymmetry parameters.

E_{slab} : E_{2D}	f_x	ℓ_{zx}	ℓ_{zy}	ξ	D_x theory	D_y theory	D_x sim.	D_y sim.	ΔD_x (%)	ΔD_y (%)
20:80	0.25	1.0	1.0	1.0	0.18260	0.21824	0.15744	0.20091	-13.78	-7.94
20:80	0.5	1.0	2.0	1.0	0.18881	0.22193	0.17234	0.20854	-8.72	-6.03
20:80	0.75	1.0	2.0	2.0	0.30971	0.11456	0.30420	0.10064	-1.78	-12.15
80:20	0.25	1.0	1.0	1.0	0.09353	0.19602	0.09823	0.19983	+5.02	+1.94
80:20	0.5	1.0	2.0	1.0	0.14387	0.19154	0.13487	0.21980	-6.26	+14.75
80:20	0.75	1.0	2.0	2.0	0.19869	0.10668	0.21412	0.10718	+7.77	+6.10

Attachment 10

Session 6

Coronal mass ejections and energetic particles



Coronal and Stellar Mass Ejections
Proceedings IAU Symposium No. 226, 2005
K. P. Dere, J. Wang & Y. Yan, eds.

doi:10.1017/S1743921305000803

Transport and Acceleration of Solar Energetic Particles from Coronal Mass Ejection Shocks

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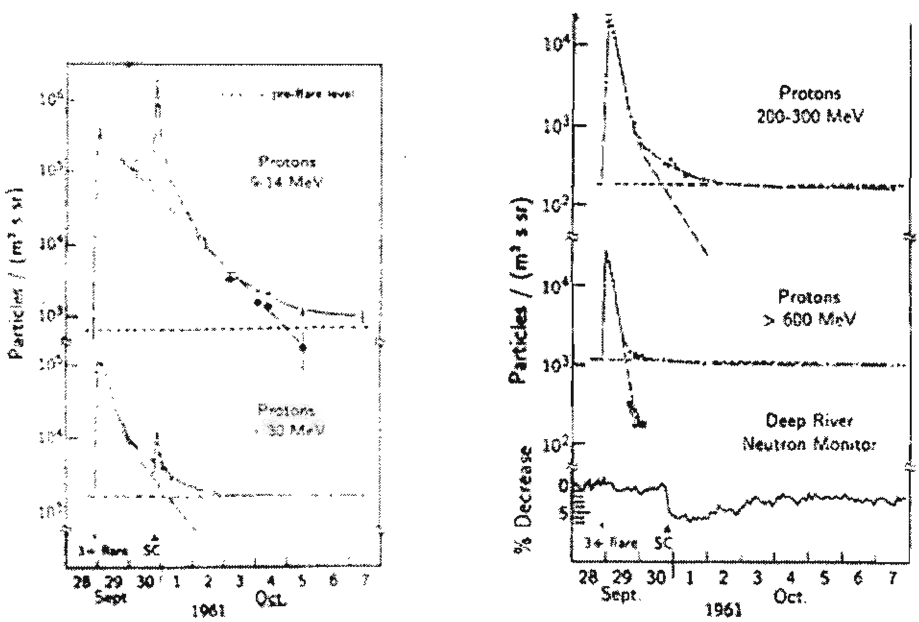
Abstract. After a brief overview of solar energetic particle (SEP) emission from coronal mass ejection (CME) shocks, we turn to a discussion of their transport and acceleration. The high energy SEP are accelerated near the Sun, and because of their well-known source location, their transport can be modeled quantitatively to obtain precise information on the injection function (number of particles emitted vs. time), including a determination of the onset time to within 1 min. For certain events, transport modeling also indicates magnetic topology with mirroring or closed field loops. Important progress has also been made on the transport of low energy SEP from very strong events, which can display exhibit interesting saturation effects and compositional variations. The acceleration of SEP by CME-driven shocks in the interplanetary medium is attributed to diffusive shock acceleration, but the spectrum of SEP production is typically modeled empirically. Recent progress has largely focused on using detailed composition measurements to determine fractionation effects of shock acceleration and even to clarify the nature of the seed population. In particular, there are many indications that the seed population is suprathermal (pre-energized) and the injection problem is not relevant to acceleration at interplanetary CME-driven shocks. We argue that the finite time available for shock acceleration provides the best explanation of the high-energy rollover.

Keywords. Sun: particle emission — Sun: coronal mass ejections (CMEs) — interplanetary medium — solar-terrestrial relations

1. Overview of solar energetic particle transport

This presentation aims to provide a brief introduction to the basic issues and some appreciation of state of the art in solar energetic particle (SEP) transport and acceleration, for a broad audience of specialists in different aspects of coronal mass ejections (CMEs).

Figure 1 shows the first report, in 1962, of energetic particles associated with an interplanetary shock, which we now believe to be driven by a CME (Bryant, Cline, Desai, *et al.* 1962). This shows the flux of protons in different energy ranges as a function of time. There are evidently two distinct populations. The first arrives shortly after the time of the flare [which we now know to be closely related to the time of CME liftoff; see Zhang *et al.* (2004)]. While the CME and shock were still very close to the Sun, protons were accelerated to several hundred MeV. On a finer timescale, SEP of higher velocity are seen to arrive first; this is termed a dispersive onset. On the other hand, there is a delayed, non-dispersive peak that dominates at low energies, associated with shock passage by the observer (in this case near Earth, as identified by a sudden storm commencement, SC). This evidently corresponds to particles accelerated by the shock as it proceeds through the interplanetary medium. These have been termed "energetic storm particles," although in recent usage both these and prompt population are referred to collectively as solar energetic particles, because at lower energies the two populations are not cleanly separated. Finally, Figure 1 shows the response of a ground-based neutron monitor, which measures the flux of galactic cosmic rays (GCR) impacting the atmosphere from a specific direction in space (by means of secondary atmospheric neutrons). Interestingly, the flux of GCR is depressed when a shock passes the Earth and sweeps these particles away. This phenomenon is known as a Forbush decrease (Forbush 1937). However, a very strong event can produce SEP to GeV energies and register an increase in neutron monitor rates; such a event is called a ground level enhancement (GLE).



(a) (b)

Figure 1. Representative proton intensities between September 28 and October 7, 1961; the decay of the solar proton event and the arrival of the energetic storm particles late on September 30 are shown. The Deep River neutron monitor record is shown for comparison. [Based on Fig. 18 of Bryant *et al.* (1962)]

There is now overwhelming physical evidence that for the class of "gradual" events that have a solar flare and a coronal mass ejection (including the geoeffective events with greatest SEP intensity), the escaping SEP are accelerated at the CME shock and not deep in the corona, e.g., not at the site of the flare or primary energy release (Mason, Gloeckler, & Hovestadt 1984; Lee & Ryan 1986; Reames 1990; Ruffolo 1997). Therefore, the two populations shown in Figure 1, with very different energy spectra, both correspond to shock acceleration, but under very different physical conditions while the shock is still close to the Sun and later as it moves in the interplanetary medium.

I would like to comment that discussions of geoeffectiveness typically stress the effects when a CME and its associated shock impact the Earth's magnetosphere, which is typically days after its liftoff from the Sun. For example, the largest SEP event of 2003 had a flare and CME on October 28 and the CME arrived at Earth on October 29. However, in a recent presentation, a NASA representative stated that more satellite anomalies occurred on October 28 than on October 29 (L. Barbieri, private communication, 2004). Therefore, the flare/CME at the Sun is immediately geoeffective in the sense of producing prompt space weather effects.

The main types of SEP populations are summarized in Table 1. In addition to the gradual events we have discussed so far, associated with a CME (and for major events, a flare as well), another type of event is an impulsive solar flare, with no associated CME. In this case the energetic particles are believed to result from stochastic acceleration, and there are very interesting compositional effects, such as enhancements in the isotope ^{3}He (Hsieh & Simpson 1970) and heavy ions (Hurford, Mewaldt, Stone, *et al.* 1975; Reames 2000) by factors up to 10^3 or even 10^4, an enhancement in electrons (Evenson, Meyer, Yanagita, *et al.* 1984; Cane, McGuire, & von Rosenvinge 1986), and high charge states (Klecker, Hovestadt, Gloeckler, *et al.* 1984; Luhn, Klecker, Hovestadt, *et al.* 1987).

Table 1. Populations of escaping solar energetic particles

Impulsive flares	CME shocks (gradual events)	
	Near Sun	Interplanetary
^{3}He enhanced, electron-rich, high ion Q	Up to high E dispersive onset	At low E non-dispersive
(stochastic acceleration)	(shock acceleration)	

2. Injection near the Sun: Precision modeling

According to Figure 1 and Table 1, SEP at high energy are almost always injected near the Sun. With this well-determined source, and given that the basic transport processes are well established, we are able to undertake precision modeling to determine transport parameters, the magnetic field configuration in space, and the injection vs. time near the Sun. We discuss transport of the interplanetary component in §4.

We describe the propagation of protons from a solar event by numerically solving a Fokker-Planck equation of pitch-angle transport that includes the effects of interplanetary scattering, adiabatic deceleration and solar wind convection (Roelof 1969; Ruffolo 1995; Nutaro, Riyavong, & Ruffolo 2001). We are assuming transport along the mean magnetic field, as expected when there is good magnetic connection between the source and the observer. Following Ng & Wong (1979), we define the particle distribution function F depending on time, t, pitch-angle cosine, μ, distance from the Sun along the interplanetary magnetic field, z, and momentum, p, as

$$F(t,\mu,z,p) \equiv \frac{d^3N}{dz\,d\mu\,dp}, \tag{2.1}$$

where N represents the number of particles inside a given flux tube. The derived transport equation takes the form:

$$\begin{aligned}
\frac{\partial F(t,\mu,z,p)}{\partial t} = &-\frac{\partial}{\partial z}\mu v F(t,\mu,z,p) - \frac{\partial}{\partial z}\left(1-\mu^2\frac{v^2}{c^2}\right) v_{\rm sw}\sec\psi F(t,\mu,z,p)\\
&-\frac{\partial}{\partial \mu}\frac{v}{2L(z)}\left[1+\mu\frac{v_{\rm sw}}{v}\sec\psi - \mu\frac{v_{\rm sw}v}{c^2}\sec\psi\right](1-\mu^2)F(t,\mu,z,p)\\
&+\frac{\partial}{\partial\mu}v_{\rm sw}\left(\cos\psi\frac{d}{dr}\sec\psi\right)\mu(1-\mu^2)F(t,\mu,z,p)\\
&+\frac{\partial}{\partial\mu}\frac{\varphi(\mu)}{2}\frac{\partial}{\partial\mu}\left(1-\mu\frac{v_{\rm sw}v}{c^2}\sec\psi\right)F(t,\mu,z,p)\\
&+\frac{\partial}{\partial p}p v_{\rm sw}\left[\frac{\sec\psi}{2L(z)}(1-\mu^2)+\cos\psi\frac{d}{dr}(\sec\psi)\mu^2\right]F(t,\mu,z,p).
\end{aligned} \tag{2.2}$$

The particle velocity is denoted by v and the solar wind velocity by v_{sw}. The angle between the field line and the radial direction is specified by the function $\psi(z)$, the focusing length by $L(z) = -B/(dB/dz)$, and the pitch-angle scattering coefficient by $\varphi(\mu)$. The simulation program to solve this equation runs in a few minutes on a personal computer.

In the next step, we can simultaneously fit observed data for the SEP intensity and anisotropy vs. time. It is computationally efficient to use least squares fitting to determine the optimal piecewise linear injection function, i.e., the rate of particle injection onto the local magnetic field line vs. time near the Sun (Ruffolo, Khumlumlert, & Youngdee 1998). We find the χ^2 values of fits for different transport assumptions to determine the optimal model. For a standard Archimedean spiral field configuration (Figure 2), typically the only parameter we vary is the interplanetary scattering mean free path. Note that anisotropy data are important for constraining the optimal scattering mean free path.

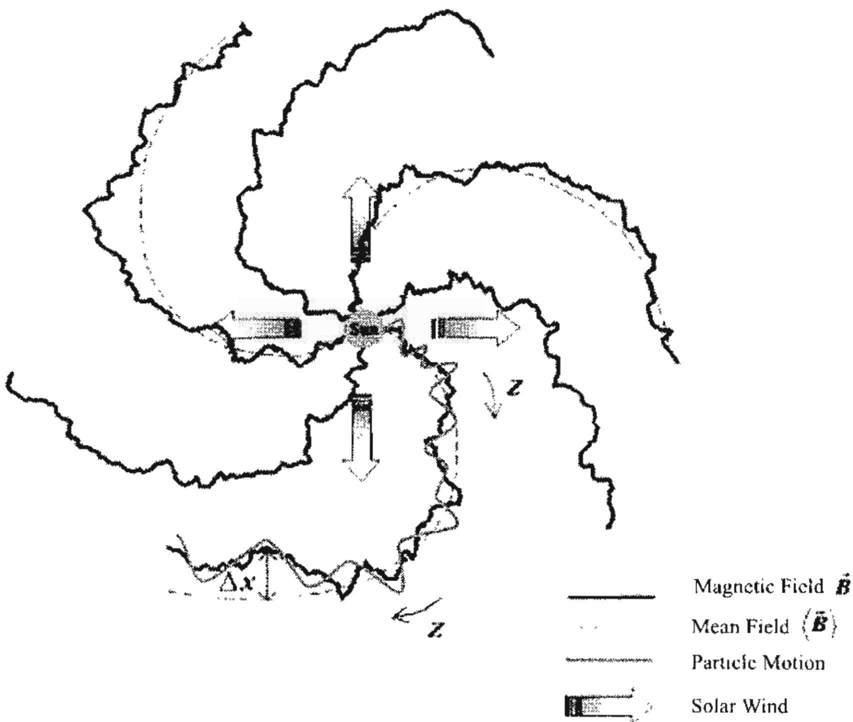


Figure 2. Typical Archimedean spiral configuration of the interplanetary magnetic field as it is dragged out of the rotating Sun by the radial solar wind.

An example of such precision modeling for the GLE of 2001 April 15 (Easter 2001) is shown in Figure 3. The intensity and anisotropy of relativistic solar protons (at rigidity ~1-3 GV) are derived from count rate increases in the *Spaceship Earth* network of polar neutron monitors, which provide high count rates and excellent directional sensitivity, and the data are then fit by the above procedure. The injection function is interpreted as the time profile of relativistic particle acceleration. Table 2 compares the injection timing with electromagnetic emissions converted into "solar time," ST, or UT minus 8 minutes to account for the propagation time. It is of particular interest that the start time of relativistic particle acceleration is coincident with the soft X-ray peak, which

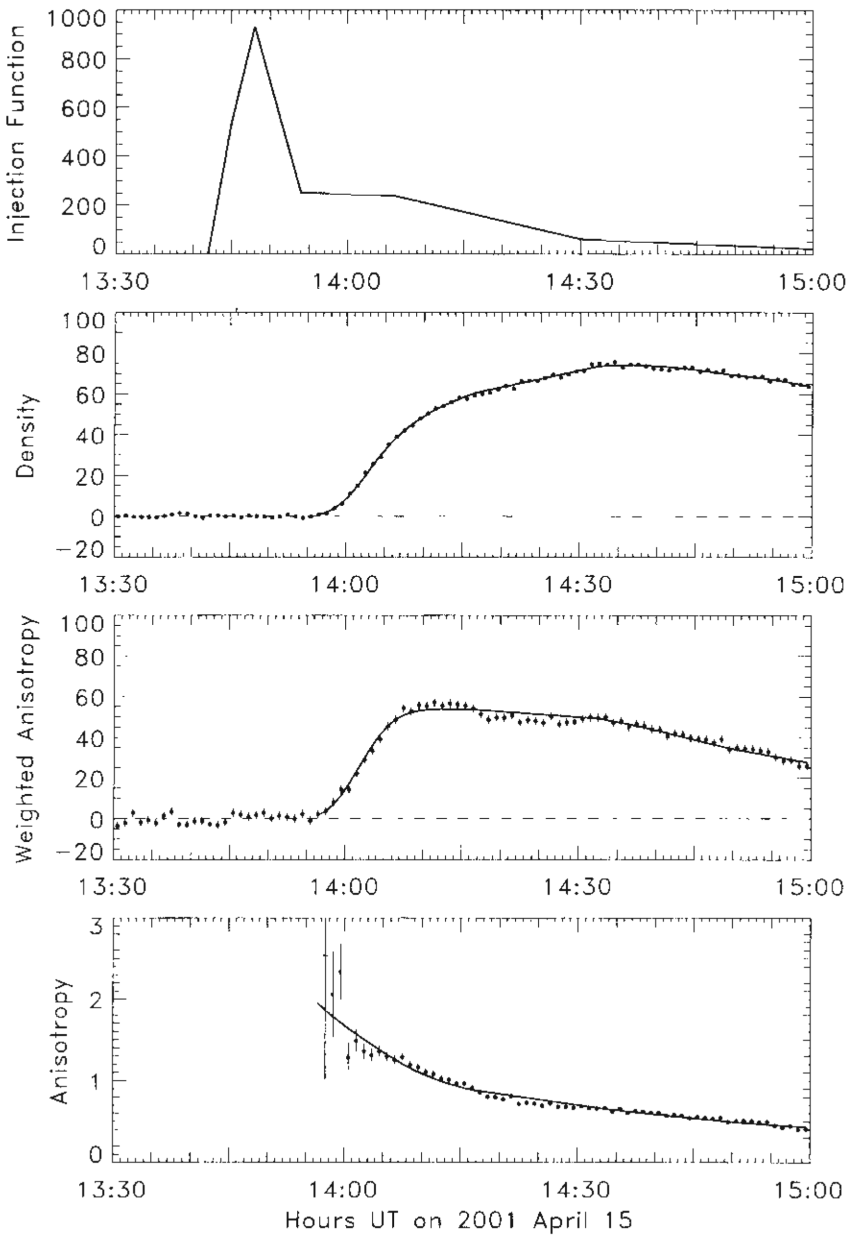


Figure 3. Precision modeling of relativistic solar proton data from neutron monitors on Easter, 2001 [Bieber, Evenson, Dröge, *et al.* (2004)].

actually marks the end of energy input in the flare. It is also later than the extrapolated CME liftoff time. Our interpretation is that the CME shock takes some time to develop and accelerate relativistic particles. Nevertheless, it does occur quite quickly; the time of relativistic particle injection corresponds to a CME altitude of only a few solar radii (Cliver, Kahler, & Reames 2004).

In some cases, such detailed fitting allows us to infer a non-standard magnetic field configuration. For example, in the GLE of 2000 July 14 (Bastille Day 2000), Bieber, Dröge, Evenson, *et al.* (2002) inferred a magnetic bottleneck configuration as in Figure 4. This corresponds to distortion of interplanetary magnetic field lines beyond the Earth by a preceding CME from the same active region a few days earlier. This is not as unusual as you might think, because major flare/CME events typically occur in sequences a few

Table 2. Timing of flare, CME, and particle emission on Easter, 2001 [Bieber *et al.* (2004)], in "solar time" (see text).

Emission	2001 April 15		
	Start	Peak	End
Relativistic protons	**13:42**	**13:48**	
Soft X-rays	13:11	13:42	13:47
Hα	13:28	13:41	15:27
Type III radio burst	13:36		13:38
CME liftoff	13:24-31		
Type II radio burst	13:40		13:47
Type IV radio burst	13:44		14:57

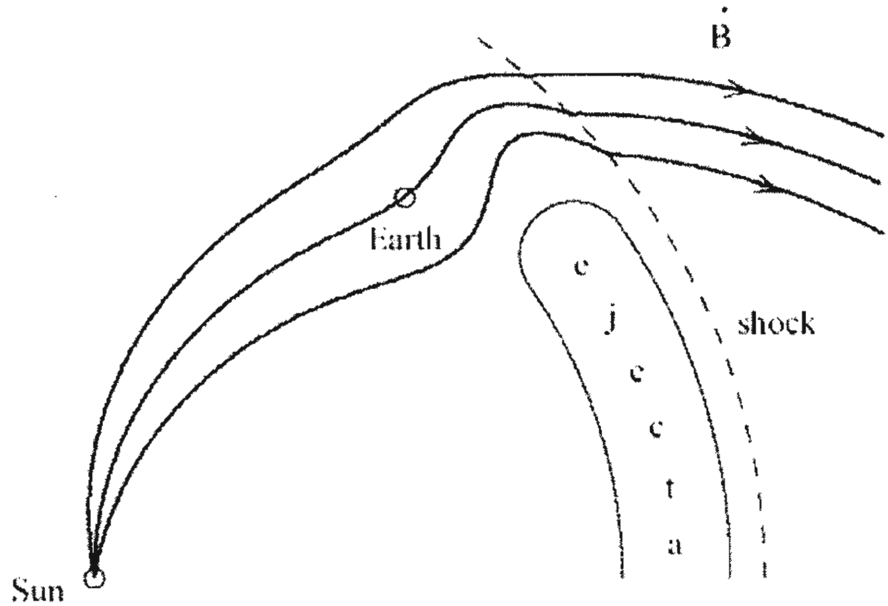


Figure 4. Magnetic bottleneck configuration inferred at the time of the Bastille Day, 2000 GLE [Bieber *et al.* (2002)].

days apart from the same active region. Indeed for two other GLEs we infer from the angular distributions that relativistic solar protons were propagating inside a magnetic loop configuration (Ruffolo, Tooprakai, Rujiwarodom, *et al.* 2004; Bieber, Clem, Evenson, *et al.* 2005). This important information about particle transport again relies on accurate measurements of directional distributions of SEP, such as those from the worldwide neutron monitor network or from rotating spacecraft with multiple sensor heads.

3. Transport perpendicular to the mean magnetic field

So far we have discussed SEP transport parallel to the mean magnetic field, commonly called "parallel transport." Another important issue is perpendicular transport, i.e., perpendicular to the mean magnetic field, which governs the latitudinal and longitudinal transport of SEP. In the classic work of Jokipii (1966), such transport is considered to be dominated by the field line random walk. As illustrated in Figure 2, the interplanetary magnetic field fluctuates strongly due to solar wind turbulence, and individual field lines can undergo a random walk that deviates quite far from the mean magnetic field. This was classically viewed as a diffusive random walk, and one can define a field line diffusion coefficient in terms of the lateral deviation Δx compared with the distance along the mean field, Δz:

$$\text{field line diffusion} \quad \rightarrow \quad D = \frac{\langle \Delta x^2 \rangle}{2\Delta z}. \tag{3.1}$$

The field line diffusion is related to the particle diffusion coefficient:

$$\text{particle diffusion} \quad \rightarrow \quad \kappa = \frac{\langle \Delta x^2 \rangle}{2\Delta t}, \tag{3.2}$$

and in the limit that particles exactly follow the field lines, one obtains $\kappa = Dv/4$.

For a realistic model of solar wind turbulence, Matthaeus, Gray, Pontius, *et al.* (1995) derived an expression for D, and Bieber & Matthaeus (1997) developed a theory for κ based on concepts of dynamical turbulence. Giacalone & Jokipii (1999) used Monte Carlo simulations to derive κ values intermediate to those for the classic field line random walk model and for dynamical turbulence. Recently, Qin, Matthaeus, & Bieber (2002) and Matthaeus, Qin, Bieber *et al.* employed numerical simulations and a nonlinear guiding center theory to show that in the ensemble average, particles undergo diffusion, then subdiffusion (also known as compound diffusion), and finally a second régime of diffusion at a slower rate.

Interestingly, Mazur, Mason, Dwyer *et al.* (2000) presented observations of SEP from impulsive flares (which are particle sources of narrow lateral extent) with "dropouts" or sudden disappearance and reappearance of flux as a function of time, which is interpreted as due to the spacecraft's motion through a filamentary distribution of magnetic flux tubes, of typical width 0.03 AU, that are filled with particles because they connect back to the source region. This shows that the lateral transport of SEP, and presumably the field lines themselves, is highly non-diffusive over a distance scale of 1 AU. To address this, Ruffolo, Matthaeus, & Chuychai (2003) replaced ensemble statistics with conditional statistics dependent on the starting point. For a standard description of solar wind turbulence, with no free parameters, they were able to simultaneously reproduce dropout structures of field lines at 1 AU connected to a small initial region and also explain the high rate of lateral diffusion κ inferred from observations by the Ulysses spacecraft (McKibben, Lopate, & Zhang 2001). The resulting picture (Figure 5) is that field lines starting near O-points in the turbulence are topologically trapped for some distance beyond 1 AU, whereas other field lines escape very rapidly. This accounts for a "core" region of outgoing SEP, with dropouts, and the SEP missing from the interstitial core regions are instead in a "halo" of low SEP density over a wide lateral region. At long radial distances all the field lines are found to escape and undergo diffusive random walks, so that particles undergo parallel and perpendicular diffusion throughout the inner heliosphere at later times.

4. Particle acceleration by coronal mass ejection shocks in the interplanetary medium

Referring to Table 1, we now turn to SEP accelerated by CME shocks traveling through the interplanetary medium (also referred to as energetic storm particles). We are fortunate to have other presenters who will show detailed results about these particles, so I will present only a broad-brush overview to help orient the non-specialist reader. While such SEP are certainly important, and also relevant to space weather effects, the underlying processes of acceleration and transport are poorly understood because they are both time-dependent and difficult to separate. (We saw in Section 1 that when acceleration and transport can be considered individually, the observations can clearly address each

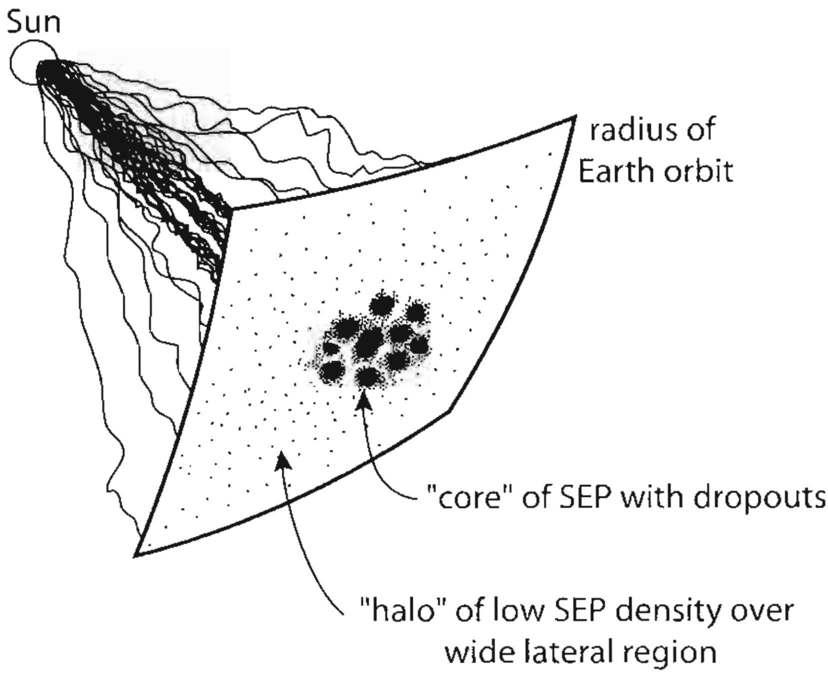


Figure 5. Illustration of the temporary trapping of magnetic field lines due to the small scale topology of solar wind turbulence [Ruffolo *et al.* 2003]. Trapped field lines form a core region with high SEP density and dropouts, while escaping field lines form a wider halo of lower SEP density. At long distances the field lines and particles ultimately escape to participate in diffusive random walks.

of them.) Modeling the simultaneous acceleration and transport of particles in the time-dependent system of a CME, shock, magnetic field topology, and magnetic fluctuations (the last of which are also affected by the particles) is necessarily difficult and involves many simplifying assumptions that are not well constrained by observations. Because of the complicated time dependence, recent research has concentrated on variations in ionic composition to probe the underlying physical processes.

That said, there have been important improvements in understanding. In a series of papers, Ng and others have examined saturation effects in very intense SEP events, based on the idea that the particles generate waves that in turn enhance interplanetary scattering and inhibit their transport. Ng, Reames, & Tylka (1999) provided a remarkable explanation of observed changes in element ratios as a function of time, confirming that wave generation probably plays a major role in these very intense events. However, other predictions of the theory, such as very intense waves and extremely low scattering mean free paths (below 10^{-3} AU) have not been confirmed by observations.

Before proceeding further, let me present a simple introduction to the process of diffusive shock acceleration. Figure 6 is a schematic of a shock, i.e., a discontinuity in fluid properties caused by a collision between fluids (or a fluid and an obstacle) with a relative speed greater the speed of sound. In general, the magnetic field (slanted lines in Figure 6) also has a different direction on the upstream and downstream sides. Usually we can enter a reference frame in which the fluid flow $\vec{u}$ is along $\vec{B}$ both upstream and downstream, called the de Hoffmann-Teller frame (de Hoffmann & Teller 1950). As the microscopic particle scatters off the ubiquitous macroscopic magnetic irregularities flowing with speed u in the space plasma, it is analogous to a game our Chinese audience knows and loves: ping-pong. If you hit the ping-pong ball with your paddle moving forward, the ball is accelerated. This is what we see occurring on the upstream side, after the head-on collision. However, if you imagine moving your paddle backwards (not that a good Chinese ping-pong player would ever do this), the ball loses energy. This is analogous to the particle's deceleration on the downstream side. However, a shock always has $u_1 > u_2$, so there is always a net gain in energy after a complete cycle. The particle has some probability of crossing and recrossing the shock plane, and a small number of particles can achieve a very high energy. Indeed, the number of particles per unit momentum, which we call the spectrum, is a power law for standard theories of diffusive shock acceleration (Drury 1983).

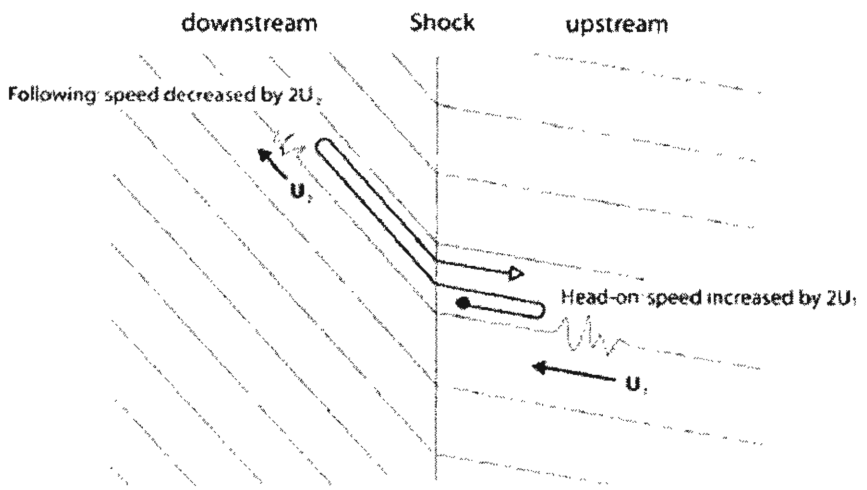


Figure 6. Illustration of diffusive shock acceleration as a particle scatters off magnetic irregularities, crossing and recrossing a shock discontinuity.

Figure 6 shows how an energetic seed particle can gain further energy at a shock. Until recently, interplanetary shocks were generally believed to accelerate particles out of the thermal solar wind population. However, there is a theoretical difficulty in understanding how thermal particles can join the shock acceleration process, the so-called "injection problem." Quite recently, Desai, Mason, Dwyer, *et al.* (2003) have analyzed the elemental composition of energetic storm particles to infer that those SEP were accelerated from a seed population of suprathermal (pre-energized) particles that happen to be upstream of the shock. Perhaps these were remnants from previous SEP events. Therefore, the injection problem is not relevant to acceleration at interplanetary CME-driven shocks.

Desai, Mason, Wiedenbeck, *et al.* (2004) have also examined the energy spectra of both the energetic storm particles and their upstream seed populations. The spectra are examined at the time of shock passage, which is one way to isolate the issue of acceleration from that of transport. They confirm a well-known rollover in the spectrum at 0.1-10 MeV nucleon^{-1} (see also Gosling, Asbridge, Bame, *et al.* 1981; van Nes, Reinhard, Sanderson, *et al.* 1985), where the power-law spectrum in particle energy changes to decline more rapidly above a critical energy, T_c. Such spectra are typically modeled empirically using the spectral form of Ellison & Ramaty (1985) for T_c as a fit parameter. However, this limit to the acceleration process is an important component of our understanding of SEP acceleration, and should be understood physically. Indeed, the critical energy must be higher near the Sun as the more energetic SEP originate there (see Table 1).

Of the possible rollover mechanisms listed by Ellison & Ramaty (1985) that might explain the rollover at 0.1-10 MeV nucleon^{-1} in the spectrum of particles accelerated by a CME-driven shock in the interplanetary medium, Ruffolo & Channok (2003) argue that the rollover is due to the finite time available for shock acceleration (see also Klecker, Scholer, Hovestadt, *et al.* 1981; Lee 1983). This allows one to derive spectra for various ionic species in terms of the physical quantities that underlie the acceleration time. For a rollover energy well above the initial energy of the seed particle, and if the mean free path λ is proportional to rigidity to the power α, one expects a rollover energy per nucleon of

$$T_c/A \propto t^{2/(\alpha+1)}(Q/A)^{2\alpha/(\alpha+1)} \tag{4.1}$$

as a function of t, the time duration of shock acceleration.

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Discussion

UNKNOWN: Comment: At the time of the 2001 April 15 event halo observations show the CME at $\sim$0.3 $R_\odot$. So if it is shock acceleration it is operating from very low heights.

RUFFOLO: Yes, I agree.

JIE ZHANG: For the two events you studied, you showed that the proton onset time is close to soft X-ray peak time. This implies that you start to see SEP at the end of CME acceleration based on my observation of CME flare relation. My question is whether the coincidence (proton onset - soft X-ray peak), is true for many other events? Any statistics on this?

RUFFOLO: We would certainly like to study more events! The analysis I showed was for data from the Spaceship Earth network of polar neutron monitors. This has only been operational, with one-minute resolution, since 2001. Thus we have only been able to analyze 3 events, the two shown here and also a small GLE on Aug. 24, For these, the proton onset is consistent with the soft X-ray peak. 2002.

SCHWENN: GeV particles accelerated near the Sun early on and MeV particles accelerated in IP space - What evidence do you have that they all came from one identical shock? There are people who think in a 2-shock scenario: 1) CME shock(driven) and 2) flare shock (blast wave), associated with Type II radio burst.

RUFFOLO: If the flare shock is delayed from the primary energy release, then we cannot rule this out based on timing alone. But let me point out that at lower ion energies, tens of MeV/n, there is strong physical evidence that the ions accelerated near the Sun came from the CME-driven shock (Mason et al, 1984, Lee & Ryan 1986, Reames 1990, Ruffolo 1997) and not from a localized source, or a source deep in the corona.

BOTHMER: There is a problem of importance: (a) Transport vs Position of the source; (b) Species: Electrons, Protons. Just a comment, not really a question.

RUFFOLO: Yes, I had actually prepared a review of these issues but I had to drop them due to a lack of time.

Finite-Time Shock Acceleration

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Abstract

Observations of energetic ion acceleration at interplanetary shocks sometimes indicate a spectral rollover at ~ 0.1 to 1 MeV/nucleon. This rollover is not well explained by finite shock width or thickness effects. At the same time, a typical timescale of diffusive shock acceleration is several days, implying that the process of shock acceleration at an interplanetary shock near Earth usually gives only a mild increase in energy to an existing seed particle population. This is consistent with recent analyses of *ACE* observations that argue for a seed population at substantially higher energies than the solar wind. Therefore an explanation of typical spectra of interplanetary shock-accelerated ions requires a theory of finite-time shock acceleration, which for long times (or an unusually fast acceleration timescale) tends to the steady-state result of a power-law spectrum. We present analytic and numerical models of finite-time shock acceleration. For a given injection momentum p_0, after a very short time there is only a small boost in momentum, at intermediate times the spectrum is a power law with a hump and steep cutoff at a critical momentum, and at longer times the critical momentum increases and the spectrum approaches the steady-state power law. The composition dependence of the critical momentum is different from that obtained for other cutoff mechanisms.

1. Introduction

The spectral form of [3], a power law in momentum with an exponential rollover in energy, has proven very useful in fitting spectra of solar energetic particles. The composition dependence of the rollover energy depends on the physical effect that causes the rollover.

For traveling interplanetary shocks well outside the solar corona, observations typically indicate a rollover at ~ 0.1 to 1 MeV/n. Let us consider what physical mechanism could explain this. If there is a cutoff for κ/u on the order of the shock thickness [3], where κ is the parallel diffusion coefficient and u is the fluid velocity along the field, the observed long mean free paths for pickup ions [4] would imply an extremely low cutoff energy. On the other hand, a cutoff due to

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shock-drift acceleration across the entire width of a shock (such as that inferred for anomalous cosmic rays) is on the order of hundreds of MeV per charge unit.

We propose that the physical origin of such rollovers is the finite time available for shock acceleration. The typical acceleration timescale t_{acc} corresponding to observed mean free paths is on the order of several days, so the process of shock acceleration at an interplanetary shock near Earth should usually give only a mild increase in energy to an existing seed particle population. Indeed, recent analyses of *ACE* observations argue for a seed population at substantially higher energies than the solar wind [1]. On the other hand, finite-time shock acceleration should yield the standard power-law spectrum in the limit of a long duration t relative to the acceleration timescale. As a corollary of this idea, for an unusually strong shock (unusually short acceleration timescale) it is possible to obtain power-law spectra up to high energies (e.g., as observed by [5]). Therefore, the present work derives a simple theory of finite-time shock acceleration and explores implications for the composition dependence of the spectrum.

2. Analytical and Numerical Models

Consider a combinatorial model of finite-time shock acceleration assuming a constant acceleration rate r (i.e., the rate of a complete cycle returning upstream, or $1/\Delta t$ of [2]) and a constant escape rate ϵ. After a time t, the distribution of residence time T is

$$P(T) = \epsilon e^{-\epsilon T} + e^{-\epsilon t}\delta(T-t). \quad (1)$$

The Poisson distribution of the number of acceleration events n during T is

$$P(n,T) = \frac{(rT)^n}{n!}e^{-rT}. \quad (2)$$

The overall probability of n acceleration events is

$$P(n,t) = \int_0^t P(n,T)P(T)dT \quad (3)$$

$$= \frac{\epsilon}{r}\left(\frac{r}{r+\epsilon}\right)^{n+1} e^{-(r+\epsilon)t} \sum_{k=n+1}^{\infty} \frac{[(r+\epsilon)t]^k}{k!} + e^{-(r+\epsilon)t}\frac{(rt)^n}{n!}. \quad (4)$$

Note that the first term is an exponential in n times a Poisson probability of $> n$ acceleration events, and the second term, corresponding to a finite probability of residence time $T = t$, is a Poisson distribution at $\langle n \rangle = rt$. Usually $\epsilon \ll r$ so the result (in terms of momentum) is a power law spectrum with a hump and subsequent cutoff after $\sim rt$ acceleration events. A more complicated analytic expression can be derived for the more realistic case where r and ϵ depend on n (and particle momentum).

Conditional Statistics of Magnetic Turbulence and the Lateral Transport of Solar Energetic Particles

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Abstract

The transport of energetic particles perpendicular to the mean magnetic field in space plasmas long has been viewed as a diffusive process. However, there is an apparent conflict between recent observations of solar energetic particles (SEP): 1) SEP from impulsive solar flares can exhibit "dropouts" in which the intensity near Earth repeatedly disappears and reappears. This indicates that the distribution of SEP in space is highly filamentary, with very little lateral diffusion across these boundaries. 2) Observations by the *IMP-8* and *Ulysses* spacecraft, while they were on opposite sides of the Sun, showed similar time-intensity profiles for many SEP events. This indicates that particles often undergo rapid lateral diffusion. We explain these seemingly contradictory observations using a theoretical model, supported by computer simulations, in which many particles are temporarily trapped within topological structures in statistically homogeneous turbulence, and ultimately escape to diffuse at a much faster rate.

1. Introduction

While spatial inhomogeneities in SEP distributions have been known for decades, they were originally attributed to large-scale disruption of magnetic connection with the Sun, e.g., magnetic sector boundaries, fast/slow solar wind boundaries, large-scale flux tubes or magnetic clouds, etc. However, the recent dropouts observed by the Advanced Composition Explorer (ACE) spacecraft for a large number of impulsive solar events [5] occur repeatedly and over such small scales (~ 0.03 AU) that they cannot be attributed to large-scale features, and instead must be related to the spatial structure of the interplanetary magnetic field [2]. Indeed, we argue that dropouts are a signature of the topology of magnetic turbulence in the solar wind. SEP from impulsive solar events serve as a good probe of lateral transport because they arise from a localized source. Particle transport perpendicular to the mean magnetic field vs. time is generally attributed to the random walk of turbulent field lines vs. distance along the mean field. However, perpendicular transport of a diffusive nature cannot explain both the dropouts and the *IMP-8*/*Ulysses* observations; the latter imply such rapid diffusion that the small-scale dropouts would be washed out. It has been proposed that fluid motions at the solar surface cause filamentary structures consistent with dropouts, but one must "switch off" the field line random walk when explaining the dropouts, and switch it on in order to explain large-scale lateral transport.

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2. Turbulence Model and Analysis of Long-Time Diffusion

We propose to reconcile these observations in terms of a two-component model of solar wind turbulence that provides a useful explanation of both its magnetic statistics and the parallel transport of SEP. This assumes a constant (or slowly varying) mean magnetic field plus two components of transverse fluctuations. The "slab" component of turbulence $\vec{b}_{slab}$ depends only on z, the coordinate along the mean field, while the "2D" component $\vec{b}_{2D}$ depends only on the perpendicular coordinates, x and y. For 2D turbulence alone, magnetic field lines can remain trapped near certain (x, y) coordinates because they always follow contours of a so-called potential function $a(x, y)$ [$\vec{b}_{2D}(x, y) = \vec{\nabla} \times [a(x, y)\hat{z}]$, where $a\hat{z}$ is the vector potential]. Figure 1 shows a contour plot of $a(x, y)$ for a specific representation of 2D turbulence with desired statistical properties (appropriate for the solar wind). The "o" symbols in Figure 1 indicate O-points [local maxima or minima in $a(x, y)$] where the contours remain trapped within "islands" of the 2D turbulence (or filaments in three-dimensional space). We also indicate X-points, i.e., saddle points of $a(x, y)$. Thus even turbulence with homogeneous statistical properties can have a topological structure.

The ensemble average statistics of the field line random walk were calculated by [4]. A diffusion coefficient, D, is defined by $\langle \Delta x^2 \rangle = 2D\Delta z$. Each turbulence component is associated with a value of D; the overall value is $D = D_{slab}/2 + \sqrt{(D_{slab}/2)^2 + (D_{2D})^2}$. Under normal solar wind conditions, D_{slab} is very small ($\approx 5 \times 10^4$ AU. As an aside, the total diffusion coefficient can be estimated from the *IMP-8* and *Ulysses* SEP data sets [3,6]. For most solar events shown by [6], the time-intensity profiles at the two spacecraft are very similar, in shape as well as absolute magnitude, immediately after the peak in particle intensity. Only Event 6 shows a distinctly diffusive rise at *Ulysses* before matching *IMP-8* data in the decay phase. Therefore we have fit this most diffusive event, using a Reid profile [9] centered at the Archimedean field line of the flare site at the radial distance of *Ulysses* (2.35 AU), to provide a lower bound on the particle diffusion coefficient $\kappa_\perp$ and (using the field line random walk concept) a conservative lower limit on D. We obtain $\kappa_\perp \geq 1.3 \times 10^{21}$ cm^2 s^{-1} and $D \geq 0.02$ AU, which are lower but of the same order of magnitude as previous estimates, e.g., [7].

In sum, we interpret that the *IMP-8* and *Ulysses* observations require a total $D > 0.02$ AU, so the 2D random walk dominates the slab random walk, and $\sqrt{\langle \Delta x^2 \rangle}$ is > 0.2 AU at Earth orbit. However, such ensemble average statistics cannot apply to observations of dropouts, because the dropouts correspond to filamentation over ~ 0.03 AU, which would be completely washed out.

Particle Acceleration at Fluid Compressions and What That Teaches Us about Shock Acceleration

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Abstract

Particle acceleration at shocks and fluid compressions is examined by numerically solving pitch angle transport equations for various magnetic field angles. The recently discovered jump in the steady-state particle density just upstream of an oblique shock is much stronger for lower energy particles or greater shock obliquity. For narrow, oblique compressions the analogous feature is a peak in particle density in the compression region. We refer to both as "mirroring peaks" because for a compression we clearly see that the peak arises from magnetic mirroring and reflection of particles. Steady-state spectra of particles accelerated at an oblique shock or compression are hardened at low energy in association with the mirroring peak; magnetic mirroring leads to more effective acceleration. The spectral index at a given particle energy increases approximately linearly with compression width. Steady-state spectra from compression regions can also harden at high energy.

1. Introduction

It is commonly believed that most cosmic rays are accelerated at astrophysical shocks. In addition to research on the acceleration of relativistic particles, there are also many open questions about the acceleration of low energy particles. Much theoretical work neglects effects of order (U/v), where U is the fluid speed relative to the shock and v is the particle speed, which are especially important for oblique shocks with a general field-shock angle [1]. For example, [3,10] have reported a jump of order (U/v) in the particle density at a shock.

The study of particle acceleration at a shock discontinuity raises the question of acceleration at continuous fluid compressions that have not yet developed into shocks. This has previously been examined for a magnetic field parallel to

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the shock normal [6]. Particle acceleration was examined in a general, steady-state context in a preliminary report by [5], while [2,4] examined the problem for the situation of corotating interaction regions and were able to explain observed time-intensity profiles.

The present work examines steady-state particle acceleration at continuous fluid compressions of varying width in comparison with that at a discontinuous shock for various shock-field angles. The configurations are shown in Fig. 1; in the compression case, magnetic field lines have a hyperbolic shape and width (semi-conjugate axis) b along the field. In comparison with shocks, the narrow compressions exhibit quantitatively similar particle acceleration, leading smoothly to the shock results as the width is reduced. However, compressions do not naturally yield a power-law particle spectrum; rather, the resulting spectrum is sensitive to the velocity dependence of the scattering mean free path. The study of acceleration at compression leads to better understanding of shock acceleration, especially regarding the effect of magnetic mirroring on the distribution function and hardening of the particle spectrum.

2. Numerical Simulations

The transport and acceleration of energetic charged particles near a fluid compression is studied by numerically solving a time-dependent pitch angle transport equation for a general, static magnetic field [11]. The numerical methods are based on those of [9,10].

For a shock the transport equation is greatly simplified, but care is required when treating particles crossing the shock. We now consider particle orbits as they cross the shock, using a transfer matrix to assign the distribution function to the appropriate μ and z cells after the shock encounter. In a stringent test of the accuracy of the pitch-angle treatment, our simulations have been able to explain observed loss-cone precursors to Forbush decreases [8].

Although the key results of this work are derived from a more fundamental treatment of pitch angle (PA) transport, we also make use of an approximate diffusion-convection (DC) treatment. The DC transport equation for the plane-parallel configuration is an ordinary differential equation, which can be solved analytically for a shock, and can readily be solved numerically for a compression. In this paper approximate DC results are shown specifically to highlight the role of magnetic mirroring, which is neglected by DC included in the full PA treatment.

3. Results

In the results, we found that particle spectra from shocks, as predicted by PA, are not exactly power laws as predicted by DC [7]. The spectra are hardened at low energy, especially for the quasi-perpendicular (Q-Perp) case (upstream

Spaceship Earth Observations of the Easter GLE

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Abstract

The ground level enhancement (GLE) of Easter (April 15) 2001 was the largest GLE of the current solar cycle, and it was also the first major event to be observed with one-minute resolution by the full eleven-station *Spaceship Earth* network of neutron monitors. We derive particle density and anisotropy profiles and model them with numerical solutions of the Boltzmann equation. Particle transport was rather diffusive in this event, with a radial mean free path ~ 0.2 AU. Particle injection onto the Sun-Earth field line began at 13:42 UT ± 1 minute, 14 minutes before the first arrival of particles at Earth.

1. Spaceship Earth

Spaceship Earth is a network of neutron monitors strategically located to provide precise, real-time, three-dimensional measurements of the cosmic ray angular distribution. As shown in Figure 1, it comprises eleven neutron monitors on four continents, deployed so as to provide good coverage of the equatorial plane as well as a north-south perspective from Thule and McMurdo. All stations have excellent directional sensitivity competitive with modern particle detectors flown in space. The name *Spaceship Earth* recognizes both the multi-national scope of the project (U.S., Russian, Australian, and Canadian participation) and the similarity of the network design to particle detectors aboard spacecraft.

An idealized version of *Spaceship Earth* was described at the Rome Cosmic Ray Conference [1]. The present network was built from seven existing stations, three new stations constructed in Canada, and one dormant station reactivated in Russia. The network became fully operational on November 10, 2000 with the opening of the station in Nain, Canada. You are invited to visit our web site ($http://www.bartol.udel.edu/\sim neutronm/$) for further details.

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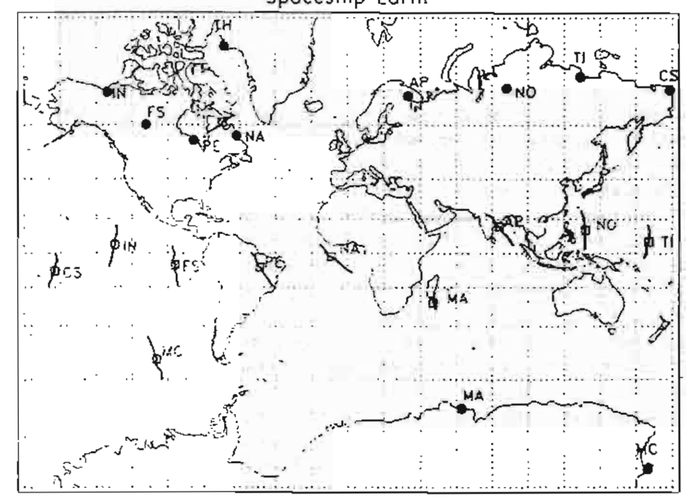

Fig. 1. Geographical locations of the eleven *Spaceship Earth* neutron monitors (circles) are displayed with the median viewing direction (squares) and range of directions (lines through squares) for each station. The lines span the central 50% of energy response, assuming a $P^{-5.1}$ rigidity (P) spectrum for the solar particles. Viewing directions were computed for a time near the start of the Easter GLE, 14:00 UT on April 15, 2001, using a trajectory code [2]. Station key: IN Inuvik, FS Fort Smith, PE Peawanuck, NA Nain, MA Mawson, AP Apatity, NO Norilsk, TI Tixie Bay, CS Cape Schmidt, MC McMurdo, TH Thule.

2. Observations

Figure 2 displays intensity-time profiles recorded by selected stations of *Spaceship Earth*. The earliest onset was recorded at Fort Smith at 13:56 UT. The profiles are roughly organized according to their viewing directions relative to the Sunward Parker spiral direction. Of the stations shown, Fort Smith was viewing most nearly along the Sunward spiral. It exhibits an early onset, fast rise, and high peak intensity. In contrast, Apatity was viewing almost directly anti-Sunward along the Parker spiral. It exhibits a late onset, gradual rise, and lower peak intensity.

Cite as: Author(s) (2004), Title, *Eos Trans. AGU, 85*(17), Jt. Assem. Suppl., Abstract xxxxx-xx

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HR: 16:30h
AN: SH24A-05
TI: Trapping of Solar Energetic Particles by Small-Scale Topology of Solar Wind Turbulence
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AB: The transport of energetic particles perpendicular to the mean magnetic field in space plasmas long has been viewed as a diffusive process. However, there is an apparent conflict between recent observations of solar energetic particles (SEP): 1) impulsive solar flares can exhibit "dropouts" in which SEP intensity near Earth repeatedly disappears and reappears, indicating a filamentary distribution of SEPs and little diffusion across these boundaries. 2) Observations by the *IMP-8* and *Ulysses* spacecraft, while they were on opposite sides of the Sun, showed similar time-intensity profiles for many SEP events, indicating rapid lateral diffusion of particles throughout the inner solar system within a few days. We explain these seemingly contradictory observations using a theoretical model, supported by computer simulations, in which many particles are temporarily trapped within topological structures in statistically homogeneous magnetic turbulence, and ultimately escape to diffuse at a much faster rate. This work was supported by the Thailand Research Fund, the Rachadapisek Sompoj Fund of Chulalongkorn University, and the NASA Sun-Earth Connections Theory Program (grant NAG5-8134).
DE: 2118 Energetic particles, solar
DE: 2134 Interplanetary magnetic fields
DE: 7807 Charged particle motion and acceleration
DE: 7859 Transport processes
DE: 7863 Turbulence
SC: SPA: Solar and Heliospheric Physics [SH]
MN: 2004 Joint Assembly

HR: 0830h

AN: SH31A-04

TI: Relativistic Solar Particles on 1989 October 22: Injection along Both Legs of a Closed Interplanetary Magnetic Field Loop

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AB: Worldwide neutron monitor observations of relativistic solar particles on 1989 October 22 have proven puzzling, with an initial spike sometimes followed by a second peak, which is difficult to understand in terms of transport along a standard Archimedean spiral magnetic field or a second injection near the Sun. Here we present an analysis of selected polar monitors, a subset of the present-day Spaceship Earth network, which provide a clean measurement of the directional distribution of solar energetic particles at ~ 1-3 GV. The

Joint Assembly
h Results

Cite as: Author(s) (2004), Title, *Eos Trans. AGU, 85*(17), Jt. Assem. Suppl., Abstract xxxxx-xx

query was:
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HR: 0830h
AN: **SH31A-05**
TI: **Finite Time Shock Acceleration at Interplanetary Shocks**

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AB: Observations of energetic ion acceleration at interplanetary shocks sometimes indicate a spectral rollover at ~ 0.1 to 1 MeV $nucl^{-1}$. This rollover is not well explained by finite shock width or thickness effects. At the same time, a typical timescale of diffusive shock acceleration is several days, implying that the process of shock acceleration at an interplanetary shock near Earth usually gives only a mild increase in energy to an existing seed particle population. This is consistent with a recent analysis of *ACE* observations that argues for a seed population at substantially higher energies than the solar wind. Therefore an explanation of typical spectra of interplanetary shock-accelerated ions requires a theory of finite-time shock acceleration, which for long times (or an unusually fast acceleration timescale) tends to the steady-state result of a power-law spectrum. We present analytic and numerical models of finite-time shock acceleration. For a given injection momentum p_0, after a very short time there is only a small boost in momentum, at intermediate times the spectrum is a power law with a hump and steep cutoff at a critical momentum, and at longer times the critical momentum increases and the spectrum approaches the steady-state

Cite as: Author(s) (2004), Title, *Eos Trans. AGU, 85*(17), Jt. Assem. Suppl., Abstract xxxxx-xx

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HR: 0830h

AN: SH31A-06

TI: Sharp Trapping Boundaries in the Random Walk of Interplanetary Magnetic Field Lines

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Cite as: Author(s) (2004), Title, *Eos Trans. AGU*, *85*(17), Jt. Assem. Suppl., Abstract xxxxx-xx

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HR: 13:50h

AN: SH33A-02

TI: Unusual Features of the October 28, 2003 Ground Level Enhancement

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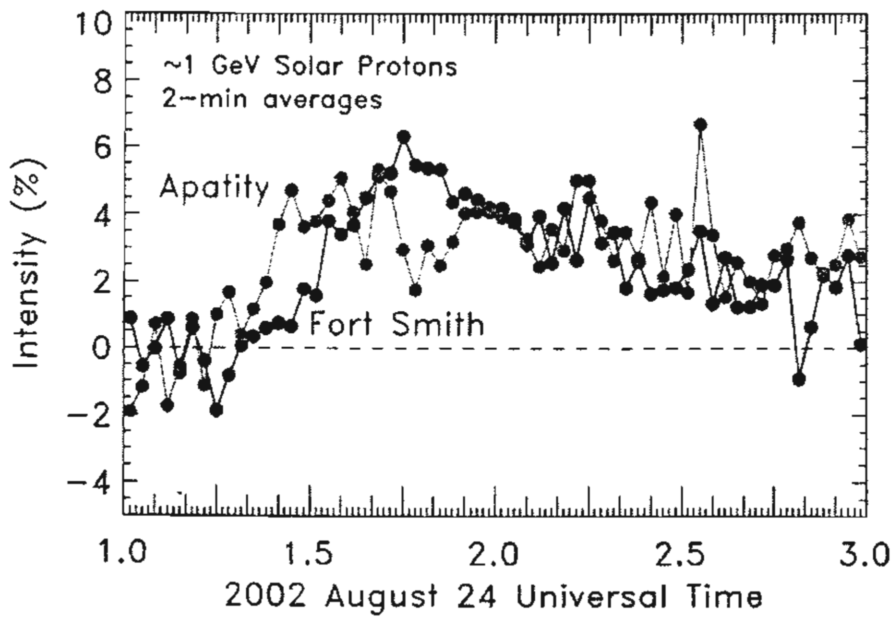
AB: The ground level enhancement (GLE) of October 28, 2003 was unusual in a number of respects. Instead of a single, anisotropic peak from the Sunward field direction followed by an isotropic decay in intensity, this event exhibited two highly anisotropic spikes from very different directions. The earliest onset was seen by Norilsk, Russia, which is surprising because this station at the time was viewing approximately anti-Sunward along the nominal Parker spiral direction. While that spike rapidly declined, another spike was observed by several neutron monitor stations, lasting about 60 minutes. This spike was also not from the Sunward field direction, but rather from a far South latitude. The decay of the event, on the other hand, was unusually slow. In fact, the particle intensity remained at elevated levels until the CME associated with the GLE arrived at Earth and swept the solar particles away. In addition, this event had an unusually hard energy spectrum compared to other GLE. We report on observations of the event made by the Spaceship Earth neutron monitor network, together with preliminary modeling of the event based on the Boltzmann equation. This work was supported by NSF grant ATM-0000315, the Thailand Research Fund, and the

SPACESHIP EARTH OBSERVATIONS OF THE 24 AUGUST 2002 EVENT (a SHINE campaign event)

J. W. Bieber, P. Evenson, R. Pyle, D. Ruffolo, and T. Khumlumlert

Earliest onset is observed by Sunward viewing stations (e.g., Apatity) ...

... but at event maximum, the highest intensities are from the anti-Sunward hemisphere (e.g., Fort Smith).



We analyze data collected by the 11-station *Spaceship Earth* neutron monitor network to derive and model the evolution of the particle density and anisotropy in this event.

Dear Dave
  Here is e-mail for submit our abstract to COSPAR.I also got the pospone deadline anouncement .

Thanks,
Manit

-------- Original Message --------
Subject: Submit abstract for Cospar2004
From: "Manit Rujiwarodom" <rmanit@sc.chula.ac.th>
Date: Fri, February 13, 2004 15:12
To: <a.devillers@colloquium.fr>, <cospar@copernicus.org>

---->(+)** +++ E-mail from Manit Rujiwarodom +++***(+)-<-----
Dear Sirs,
  This is the frist time for me to jions to COSPAR assembly.
  I like to submit our abstarct for 35th COSPAR2004 at Paris FRANCE. 18-25 July 2004.Please tell my if any problems or suggestions.

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Relativistic Solar Particles on 1989 October 22: Injection along Both Legs of a Closed Interplanetary Magnetic Field Loop

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Worldwide neutron monitor observations of relativistic solar particles on 1989 October 22 have proven puzzling, with an initial spike sometimes followed by a second peak, which is difficult to understand in terms of transport along a standard Archimedean spiral magnetic field or a second injection near the Sun. Here we present an analysis of selected polar monitors, a subset of the present-day Spaceship Earth network, which provide a clean measurement of the directional distribution of solar

energetic particles at ~ 1-3 GV. The omnidirectional intensity dips after the initial spike, followed by a nearly isotropic hump and a slow decay. The intensity and anisotropy data are fit by simulating the particle transport for various magnetic field configurations and determining the best-fit injection function near the Sun. The data are not well fit for a magnetic bottleneck beyond Earth or for particle injection along one leg of a closed magnetic loop. A model with simultaneous injection along both legs of a closed loop provides the best explanation: particles moving along the near leg make up the spike, those coming from the far leg make up the hump, and trapping in the loop accounts for the slow decay of the intensity. This work was supported by the Thailand Research Fund, the Rachadapisek Sompoj Fund of Chulalongkorn University, and NSF grant ATM-0000315.
++

This for Scientific Commission D1.3/E2.4 Energetic particle accelertion.

I will find financial support from my University.Please sent me an accept ed letter for oral presentation and reply me soon.

Best regards
From
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http://www.ThaiSpaceWeather.com
<<++(+)*** ++ Thanks...End of E-mail from Manit +++ ***(+)++>>>

Coronal and Stellar Mass Ejections
Proceedings IAU Symposium No. 226, 2005
K. P. Dere, J. Wang & Y. Yan, eds.

DOI: 10.1017/S1743921305000803

Transport and Acceleration of Solar Energetic Particles from Coronal Mass Ejection Shocks

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Abstract. After a brief overview of solar energetic particle (SEP) emission from coronal mass ejection (CME) shocks, we turn to a discussion of their transport and acceleration. The high energy SEP are accelerated near the Sun, and because of their well-known source location, their transport can be modeled quantitatively to obtain precise information on the injection function (number of particles emitted vs. time), including a determination of the onset time to within 1 min. For certain events, transport modeling also indicates magnetic topology with mirroring or closed field loops. Important progress has also been made on the transport of low energy SEP from very strong events, which can display exhibit interesting saturation effects and compositional variations. The acceleration of SEP by CME-driven shocks in the interplanetary medium is attributed to diffusive shock acceleration, but the spectrum of SEP production is typically modeled empirically. Recent progress has largely focused on using detailed composition measurements to determine fractionation effects of shock acceleration and even to clarify the nature of the seed population. In particular, there are many indications that the seed population is suprathermal (pre-energized) and the injection problem is not relevant to acceleration at interplanetary CME-driven shocks. We argue that the finite time available for shock acceleration provides the best explanation of the high-energy rollover.

Keywords. Sun: particle emission — Sun: coronal mass ejections (CMEs) — interplanetary medium — solar-terrestrial relations

1. Overview of solar energetic particle transport

This presentation aims to provide a brief introduction to the basic issues and some appreciation of state of the art in solar energetic particle (SEP) transport and acceleration, for a broad audience of specialists in different aspects of coronal mass ejections (CMEs).

Figure 1 shows the first report, in 1962, of energetic particles associated with an interplanetary shock, which we now believe to be driven by a CME (Bryant, Cline, Desai, *et al.* 1962). This shows the flux of protons in different energy ranges as a function of time. There are evidently two distinct populations. The first arrives shortly after the time of the flare [which we now know to be closely related to the time of CME liftoff; see Zhang *et al.* (2004)]. While the CME and shock were still very close to the Sun, protons were accelerated to several hundred MeV. On a finer timescale, SEP of higher velocity are seen to arrive first; this is termed a dispersive onset. On the other hand, there is a delayed, non-dispersive peak that dominates at low energies, associated with shock passage by the observer (in this case near Earth, as identified by a sudden storm commencement, SC). This evidently corresponds to particles accelerated by the shock as it proceeds through the interplanetary medium. These have been termed "energetic storm particles," although in recent usage both these and prompt population are referred to collectively as solar energetic particles, because at lower energies the two populations are

Cite abstracts as **Author(s) (2004), Title, *Eos Trans. AGU*, *85*(47), Fall Meet. Suppl., Abstract xxxxx-xx**

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HR: 1340h

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TI: Investigation of the Solar Neutron Event at Tsumeb on 28 October 2003

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AB: During the 28 October 2003 solar energetic particle event, the high rigidity cutoff (low latitude) neutron monitor located at Tsumeb in Namibia recorded a flux increase of 3-4 percent roughly 10 minutes before the onset of a Ground Level Event (GLE) observed by many low rigidity cutoff (high latitude) neutron monitors. An analysis of the properties of this neutron event is presented, based on direct neutrons produced in the lower solar atmosphere by hadronic interactions. After deriving the yield function for neutrons at Tsumeb and using a typical spectrum for

48. Coronal radio bursts

S. M. White, T. S. Bastian and R. Bradley

Paper for the topic "Radio Observations of CMEs and Particle Acceleration": we will discuss the relationship between solar radio bursts, CMEs and particle acceleration using results from the Green Bank Solar Radio Burst Spectrometer where possible to illustrate the discussion.

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49. Radio Observations Related to CMEs and to Particle Acceleration

Mike Reiner

It has been known since the 1950's that coronal shocks and particle acceleration produce distinct radio signatures that can be remotely observed by ground-based and spaced-based radio observatories. The so-called type II radio bursts are generated by coronal shocks and can provide information on the origin and kinematics of these moving disturbances. On the other hand, the so-called type III radio bursts are associated with accelerated electrons. They therefore provide information on the origin and timing of particle acceleration sites in the corona, which can be directly compared to the in-situ particle observations. Although the details of the processes and conditions necessary for generating type II and type III emissions are not precisely known, they can nevertheless be used, particularly in conjunction with constraints provided by other complementary observations, to yield crucial information on solar energetic solar processes. For example, since major CME/flare events generally produce both type II and type III radio emissions, these observations can clarify the relationship between the CME and coronal particle acceleration.

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50. Finite time shock acceleration and fits to ESP ion spectra

David Ruffolo, Mahidol University

Chanruangrit Channok (1,2,3), David Ruffolo (2), Mihir Desai (4), and Glenn Mason (4) - (1) Department of Physics, Chulalongkorn University, Bangkok, Thailand (2) Department of Physics, Mahidol University, Bangkok, Thailand (3) Department of Physics, Ubonrajathanee University, Ubonrajathanee, Thailand (4) Department of Physics, University of Maryland, College Park, Maryland, USA

Energetic storm particles (ESP) of various ion species have been shown to comprise suprathermal seed ions accelerated by traveling interplanetary shocks. The observed spectral rollovers at ~0.1 to 10 MeV $nucleon^{-1}$ can be attributed to the finite time available for shock acceleration. Using the locally measured shock strength parameters as inputs, the finite-time shock acceleration model can successfully fit the energy spectra of carbon, oxygen, and iron ions measured by ACE/ULEIS during 3 ESP events. The inferred scattering mean free path in the acceleration region ranges from typical interplanetary values for the weakest ESP events down to 4.0×10^{-3} AU for the strongest event. This is consistent with the idea that proton-amplified waves result from the very intense particle fluxes in major events.

Work in Thailand was supported by the Commission for Higher Education, the Rachadapisek Sompoj Fund of Chulalongkorn University, and the Thailand Research Fund. Work at the University of Maryland was supported by NASA contract NAS5-30927 and NASA grant PC 251428.

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107. Relativistic Solar Protons on 1989 October 22: Injection along Both Legs of a Loop

David Ruffolo (1), Paisan Tooprakai (2), Manit Rujiwarodom (2), Thiranee Khumlumlert (3), Maneenate Wechakama (4), John Bieber (5), Paul Evenson (5), & Roger Pyle (5) - (1) Department of Physics, Mahidol University, Bangkok , Thailand (2) Department of Physics, Chulalongkorn University, Bangkok, Thailand (3) Department of Physics, Naresuan University, Phitsanulok, Thailand (4) Department of Physics, Kasetsart University, Bangkok, Thailand (5) Bartol Research Institute, University of Delaware, Newark, DE

Worldwide neutron monitor observations of relativistic solar protons on 1989 October 22 have proven puzzling, with an initial spike at some stations followed by a hump with bidirectional flows and a very slow decay. We analyze data from polar monitors, which measure the directional distribution of solar energetic particles (mainly protons) at rigidities of ~1-3 GV. The inferred density and anisotropy are simultaneously fit by simulating the particle transport for various magnetic field configurations and determining the best-fit injection function near the Sun. The data are not well fit for an Archimedean spiral field, a magnetic bottleneck beyond Earth, or particle injection along one leg of a closed magnetic loop. A model with simultaneous injection along both legs of a closed loop provides the best explanation. Refined fits indicate a very low spectral index of turbulence, $q<1$, and hence an unusually low correlation length of magnetic fluctuations in the loop, a parallel scattering mean free path of 1.2 to 2 AU, a loop length of 4.7+/-0.3 AU, and escape from the loop on a time scale of 3 hours.
Partially supported by the Thailand Research Fund, the Rachadapisek Sompoj Fund of Chulalongkorn University, and the US National Science Foundation (grant ATM-0000315).

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108. Comparison of Solar Energetic Particle Events and Impulsive Nitrate Increases in Arctic Ice Cores

H. E. Spence (1), L. Kepko (1), M. A. Shea (2), and D. Smart (2)

Previous studies suggest that historic, large solar proton events have been identified in high time-resolution (decimal year) nitrate records in arctic ice cores. It has been proposed that spikes in ice core nitrate concentration are produced by the precipitation of an elevated, impulse of middle atmospheric nitrates. Consequently, ice core nitrates have the potential to track the processes which create atmospheric nitrates, including those known to be associated with major, impulsive solar proton events (i.e., those with significant fluxes > 30 MeV). In an attempt to explore and to validate these previous results we have examined shallow (~30 meter depth) ice cores obtained in June 2004 from Summit, Greenland. Thirty meter depth cores at Summit span the time period from ~1930 to present. We report on high-resolution nitrate analysis of these ice cores using a continuous flow analysis system designed, built, and in operation at Boston University. We examine the correlation between impulsive nitrate spikes in the ice strata and solar proton events over the past ~75 years. For this comparison, we appeal to ground-level-enhancement cosmic ray observations in the era before in situ spacecraft observations of solar protons were available. We report on the amplitude and timing of measured ice core nitrate increases in relation to the onset and characteristics of known (or inferred) SEP events. A time delay between nitrate spikes and SEP onset has previously been observed to be a few weeks, which is much faster than current atmospheric downward transport theory allows. Independent assessment of these previously-determined time delays will also be presented.

87. Turbulence, dropouts, and suppression of the field line random walk

David Ruffolo (1), Piyanate Chuychai (1,2,3), William H. Matthaeus (3), and George Rov
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University of Delaware, Newark, DE, USA (4) Department of Physics, University of Wa
wick, Coventry, UK

We employ the well-tested two-component model of solar wind turbulence to explain dro
outs in impulsive SEP events over distances ~1 AU from the Sun, while at longer distanc
much faster diffusive transport is found. Magnetic field lines are temporarily trapped in fi
ments defined by the small-scale topology of the 2D component of turbulence (fluctuatic
with perpendicular wave vectors). Within such islands, the 2D component does not contr
ute to the random walk, which therefore takes place at the much slower rate for the slab co
ponent (fluctuations with parallel wave vectors). A further consideration is that both o
served and simulated dropouts occur very sharply. We provide computational evidence an
theoretical explanation that strong 2D turbulence can inhibit diffusion due to the slab comp
nent. Therefore, while the dropout filaments are basically defined by the small-scale topolc
of 2D turbulence, there can be sharp trapping boundaries where the 2D field is strongest. P
tially supported by the Thailand Research Fund and the NASA Sun-Earth Connections Th
ory Program (grant NAG 5-8134).

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88. Solar Cycle Variation of the Properties of Interplanetary Coronal Mass Ejection (ICMEs)

C. T. Russell, L. Jian, J. T. Gosling, and J. G. Luhmann

In the poster "A New Parameter for Characterizing ICMEs" for 2004 SHINE meeting,
advocated the use of the total perpendicular pressure for ICME studies. We classified Int
planetary Coronal Mass Ejections (ICMEs) into three groups depending on the behavior
the perpendicular pressure, which itself may be controlled by the impact parameter of t
spacecraft passing through the ICME relative to the center of the flux rope. Though there a
indeed some weak and spent ICMEs at 1 AU that may not have pressure signatures, we ha
used these signatures in the pressure to identify ICMEs and characterize them. We give t
occurrence rate, peak pressure and the maximum magnetic field of the three groups
ICMEs based on the study of 9 years WIND data, to determine if concept of an impact p
rameter dependent signature can explain the conventional wisdom that only about one-th
of ICMEs are found to contain a magnetic cloud. In addition, we give the solar cycle var
tion (1995-2003) of the number of identified ICME events, the percentage of events w
shocks, the distribution of the change in the velocity of events, and the distribution of t
peaks of the magnetic field and total perpendicular pressure. Basically, the peak pressu
grows over the rising phase of the solar cycle and becomes greatest at solar maximum, pr
ducing the strongest interaction with the Earth's magnetosphere at solar maximum.

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95. A statistical study 0f high energetic (~90 MeV) proton events observed with SOHO/ERNE during solar cycle 23

Amjad Al-Sawad, Jarmo Torsti, Leon Kocharov, and Kalle Huttunen-Heikinmaa

During the period of SOHO observation for the solar cycle 23 we selected 51 energetic proton events with energies of (79.2-114), (80,2-101) and (86.7-101) MeV and intensities of > [10^-3/(cm^2.sr.s.MeV/n)] detected by Energetic and Relativistic Nuclei and Electrons (ERNE) onboard SOHO. We exam the first injection time of those events through two methods, first by estimating the flight time of non-scattered protons of those nominal energies along the Archimedean field line of nominal length 1.2 AU. Secondly by considering more possible wide range of proton energies for the same events and assume a simultaneous release and that the path length does not depend on the energies. Those events were associated with CMEs observed simultaneously with Large Angle and Spectrometric Coronagraph (LASCO) and solar flare observed with soft X-ray telescope onboard GOES. We find that most of those events are due to CMEs and 84% of those CMEs (43/51) were associated with solar flares. The solar flares were 49% of class X, 47% of Class M, and 4% of class C. The mean value of speed and angular width of those CMEs associated with X-class flare are higher than those which associated with the M-class. 79% 0f those CMEs located at heliocentric location between (1-5) solar radii at the time of first proton injection of >90 MeV energy, and 84% located at over 10 solar radii at the time of maximum intensity, and those maximum intensities were achieved much earlier than the possible IP sock passage in mean time difference between onset and maximum of 4 hours. 3 events were excluded for suspicion of the source of the first injected protons. From the whole CMEs about 82\% (42/51) were located on the west side of the sun. 94\% were associated with metric radio emission of type II or/and IV and/or DH type. Average speed and angular width decreases as the CMEs associated with metric/DH type II and IV, only metric type II and IV, No association of any metric or DH radio emission. About 61% of those CMEs were halo. The highest intensity were achieved with halo CMEs acceded 1000 km/s and with those events associated with X class flare. The proton production of energetic protons of nominal >90 MeV seems to start with flare and CME-liftoff processes in low corona and continues during CME propagation farther from the Sun

96. Record-Setting Ground Level Enhancement: January 20, 2005

John W Bieber, Bartol Research Institute, University of Delaware
Full Author List: John W Bieber(1), John Clem(1), Paul Evenson(1), Roger Pyle(1), Marc Duldig(2), John Humble(3), David Ruffolo(4), Alejandro Sáiz(4,5), and Manit Rujiwarodom(5)
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Within a 6-minute span on January 20, 2005, the count rate registered by a neutron monitor at the sea level station of McMurdo, Antarctica increased by a factor of 30, while the rate at the high-altitude (2820 m) site of South Pole increased by a factor of 56. The size of the increase at McMurdo qualifies it as the largest observed at sea level since the famous 1956 event, while the increase at South Pole may have been the largest (in percentage terms) ever registered by a neutron monitor. This paper uses data from the "Spaceship Earth" network of neutron monitors to characterize and model the time evolution of cosmic ray density and anisotropy during the event of January 20, 2005. Supported by NSF grant ATM-0000315, the Thailand Research Fund, and the Rachadapiseck Sompoj Fund of Chulalongkorn University.

97. Energy Dependent Broadening of Low-Energy Solar Electron Bursts

Curt A. de Koning, S. Peter Gary, J. T. Gosling, Ruth M. Skoug, John T. Steinberg, LANL

Solar active processes frequently produce electron bursts which, at 1 AU, extend to energies less than 1.4 keV. The characteristics of these solar electron bursts vary considerably from event to event due to the physical processes involved in their acceleration and propagation to Earth. Previous observations have shown that some bursts have a broader field-aligned pitch-angle distribution than the preceding strahl, suggesting that propagation effects are important for understanding 1 AU observations. We present a study of suprathermal electron pitch-angle distributions observed in 2002 by ACE/SWEPAM before, during, and after solar bursts. We find that 41 of 72 bursts observed at energies less than or equal to 713 eV broaden. Prior to the burst onset, 60 of the bursts had a half width half maximum (HWHM) less than 40 degrees. Fourteen of the broadened bursts had a HWHM which exceeded 60 degrees. These width characteristics stand in marked contrast to previously published results for solar burst electrons in the 2-15 keV range which consistently found that the electrons were highly beamed along the magnetic field direction with HWHM less than 15 degrees. Typically, we observe that the width of the burst suprathermal electron distribution increases with increasing energy up to 1.4 keV. The observed energy dependence and the beamed distributions above 2 keV suggest that the scattering rate for electrons as a function of energy has a maximum between 1 and 2 keV. Computer simulations based on bi-Maxwellian core and halo distributions suggest that electron-driven instabilities cannot explain the observed beam broadening. We discuss the role of pitch-angle scattering by ambient whistler turbulence in the dissipation range as a mechanism for the energy dependence of the beam broadening.

98. Observation of Neutron and Gamma Ray Emission from the October 28, 2003 Solar Flare

Paul Evenson, University of Delaware

John Bieber, John Clem, Paul Evenson and Roger Pyle, all at Bartol Research Institute, University of Delaware, Newark, Delaware J. Bernard Blake and Tamitha Mulligan, both at Space Sciences Department, The Aerospace Corporation, Los Angeles, California David Ruffolo, Department of Physics, Faculty of Science, Mahidol University, Bangkok, Thailand Alejandro Saiz, Department of Physics, Faculty of Science, Mahidol University, Bangkok, Thailand and Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand

Recently we published an analysis of the response of the Tsumeb neutron monitor to the large solar flare of October 28, 2003. (GRL doi:10.1029/2004GL021492, 2005) We concluded that the flare produced neutrons over an extended interval of approximately seven minutes. Gamma-rays observed from the SAMPEX spacecraft now confirm the extremely long duration of energetic emission from this event. Both POLAR and SAMPEX have detected protons that may have resulted from the decay of neutrons emitted by this flare. We use these data to determine the energy spectrum of neutrons emitted by the flare, and to further refine our calculation of the time structure of the emission. We compare the emission time structure of the neutrons and gamma-rays with available optical data, and with the injection profile of the GeV interplanetary protons in an attempt to identify the source region of this energetic radiation. Supported in part by NSF grant ATM 0000315, the Thailand Research Fund, and the Ratchadapisek Sompoj Fund of Chulalongkorn University.

29th International Cosmic Ray Conference Pune (2005) 00, 101–106

Relativistic Solar Protons on 1989 October 22: Injection and Transport along Both Legs of a Closed Interplanetary Magnetic Loop

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Worldwide neutron monitor observations of relativistic solar protons on 1989 October 22 have proven puzzling, with an initial spike at some stations followed by a hump with bidirectional flows and a very slow decay. We analyze data from polar monitors, which measure the directional distribution of solar energetic particles (mainly protons) at rigidities of ~1-3 GV. The inferred density and anisotropy are simultaneously fit by simulating the particle transport for various magnetic field configurations and determining the best-fit injection function near the Sun. The data are not well fit for an Archimedean spiral field, a magnetic bottleneck beyond Earth, or particle injection along one leg of a closed magnetic loop. A model with simultaneous injection along both legs of a closed loop provides the best explanation. Refined fits indicate a very low spectral index of turbulence, $q < 1$, and hence an unusually low correlation length of magnetic fluctuations in the loop, a loop length of 4.7 ± 0.3 AU, and escape from the loop on a time scale of 3 hours.

1. Introduction

The observations of relativistic solar protons by ground-based neutron monitors on 1989 October 22 have defied conventional explanations and proven mysterious for 15 years. Observations of relativistic solar protons during a ground-level enhancement (GLE) typically begin with a rapid, anisotropic onset, with most particles moving anti-Sunward along the interplanetary magnetic field. Because of pitch-angle scattering, which eventually leads to spatial diffusion, the distribution becomes more isotropic with time, and gradually decreases (or "decays") as particles diffuse out of the inner heliosphere. However, the GLE of 1989 October 22 had an extraordinary spike at onset, which was highly anisotropic. The event was also unusual in exhibiting a second peak, which we call the "hump," an hour after the initial spike, followed by a very slow decay.

While the spike can be interpreted [1] as the "coherent pulse" predicted by focused transport theory [2] for conditions of weak scattering (i.e., a long scattering mean free path), the hump and slow decay have proven more difficult to understand. Ref. [3] considers propagation along a standard Archimedean spiral field and two separate injections of particles at the Sun. However, a detailed analysis reveals bidirectional fluxes in the hump [4], which along with the slow decay is not explained by the model of [3]. A different line of reasoning was presented by [4, 5], who explained the spike and hump in terms of a "disturbed plasma region" beyond Earth that scattered particles back. The outward component of the bidirectional flow is attributed to extended solar injection. Actually, a more efficient type of backscattering is mirroring by a magnetic bottleneck beyond Earth; [6] show evidence for this process during the GLE of Bastille Day 2000. In the present work, we consider various magnetic configurations that might explain this mysterious data set.

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On the Estimation of Solar Energetic Particle Injection Timing from Onset Times near Earth

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A common technique for estimating the start time of solar energetic particle (SEP) injection consists of a linear fit to the observed onset time versus the inverse of particle velocity. This is based on a concept that the first arriving particles move directly along the magnetic field with no scattering. We examine the accuracy of this technique by performing numerical simulations of the transport of solar protons of different energies from the Sun to the Earth, by means of a finite difference method to numerically solve the Boltzmann equation. We then analyze the results using the inverse velocity fit. We find that in most cases, the onset times align close to a straight line as a function of inverse velocity. Despite this, the estimated injection time can be in error by several minutes. Also, the estimated path length can deviate greatly from the actual path length along the interplanetary magnetic field. The major difference between the estimated and actual path lengths implies that the first arriving particles cannot be viewed as moving directly along the interplanetary magnetic field.

1. Introduction

An important issue when studying solar events is the exact time when SEPs are first released from the Sun or its vicinity, t_0. When inferring this, one has to take into account the many different processes acting on the SEPs from their release until the time of detection, t_{onset}, at spacecraft or Earth-based instruments. These include the finite duration of injection at the Sun, the streaming along the interplanetary (IP) magnetic field, the pitch-angle scattering due to resonant interactions with magnetic field irregularities, and effects due to the solar wind speed, such as convection and adiabatic deceleration. These various effects can be taken into account to precisely determine the start time of injection at the Sun [1].

A popular approximation is to consider that the first observed SEPs move approximately parallel to the mean magnetic field. By doing this one neglects the effects of IP scattering at onset. Then, combining measurements at different energies, both the injection time and the path length travelled by the SEPs (typically interpreted as distance along the magnetic field from the Sun to the Earth) are estimated from a fit of the detection onset times and inverse velocities to a straight line. This "onset time versus $1/\beta$" method has already become a common practice [2], reinforced by the generally good alignment of experimental data along a straight line in this plot.

However, the basic hypothesis of negligible scattering and motion at zero pitch angle is hard to reconcile with the well-established theories of particle transport. Considerable delays in the detected onset can arise both from IP scattering and a finite duration of the particle injection [3]. The onset time can also be affected by other physical processes such as solar wind convection, and also by the technical difficulties in measuring the onset above the pre-event particle background. In this paper we investigate the validity and systematic error of the approximation that the first arriving SEPs have undergone no scattering. We employ state-of-the-art numerical simulations of particle transport, and analyze the resulting onset time versus inverse velocity. We then compare the estimated start time of injection at the Sun and path length with those actually used in the simulation to estimate the systematic error in the estimated values.

29th International Cosmic Ray Conference Pune (2005) **00**, 101–106

Relativistic Particle Injection and Interplanetary Transport during the January 20, 2005 Ground Level Enhancement

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Besides producing the largest ground level enhancement (GLE) in half a century, the relativistic solar particles detected during the event of January 20, 2005 showed some interesting temporal and directional features, including extreme anisotropy. In this paper we analyze the time evolution of cosmic ray density and anisotropy as characterized by data from the "Spaceship Earth" network of neutron monitors by using numerical solutions of the Fokker-Planck equation for particle transport. We find that a sudden change in the transport conditions during the event is needed to explain the data, and we propose that this change was caused by the solar particles themselves.

1. Introduction

The remarkable solar event of 2005 January 20 produced the highest flux of relativistic solar particles observed at many neutron monitor stations for nearly 50 years [1]. This event provides an opportunity to measure relativistic solar particle fluxes with high statistical accuracy, and in particular the recently completed Spaceship Earth network of polar neutron monitors with uniform detection characteristics [2] provides a precise determination of the directional distribution. It was particularly fortunate that a spectacular increase of $\sim 5500\%$ was observed at the South Pole station, where the Polar Bare counters, which are preferentially sensitive to particles at sub-GV rigidity, are operated along with a standard 18-NM-64 monitor, providing a special opportunity to measure the spectrum with unparalleled precision.

In addition, one might expect special physical effects in association with the extremely high flux of relativistic particles in space. Indeed, our preliminary results indicate what may be the first documented example of nonlinear transport processes of relativistic solar particles. Applying existing techniques to model the interplanetary transport of solar particles [3] and fit time profiles of particle density and weighted anisotropy [4] as determined from polar neutron monitors worldwide [5], there is a clear indication of two enhancements in particle flux at Earth, the second of which has a much lower anisotropy. The most natural explanation is that the change in transport conditions was caused by the particles themselves, which generated waves that resonantly scattered the particles injected later in the event.

2. Injection and transport modelling

First, data from 12 polar neutron monitor stations situated worldwide [5] are fit to an analytic function of the particles' pitch angle about an optimal axis of symmetry taking into account bending of particle trajectories in Earth's magnetic field. The omnidirectional intensity and weighted anisotropy (standard anisotropy multiplied by intensity) are extracted as quantities to be fit by the transport model. Two peaks, separated by an 8 minute

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Largest GLE in Half a Century: Neutron Monitor Observations of the January 20, 2005 Event

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Within a 6-minute span on January 20, 2005, the count rate registered by a neutron monitor at the sea level station of McMurdo, Antarctica increased by a factor of 30, while the rate at the high-altitude (2820 m) site of South Pole increased by a factor of 56. The size of the increase at McMurdo qualifies it as the largest observed at sea level since the famous 1956 event, while the increase at South Pole may have been the largest (in percentage terms) ever registered by a neutron monitor. This paper uses data from the "Spaceship Earth" network of neutron monitors to characterize the time evolution of cosmic rays during the event. We also investigate spectral evolution using multiplicity data from a specially instrumented mobile monitor that was located in McMurdo Sound at the time of the event.

1. Introduction

The Sun occasionally emits cosmic rays of sufficient energy and intensity to increase radiation levels on the surface of Earth. From the time systematic observations by neutron monitors began in the 1950's, such "ground level enhancements" (GLE) have occurred at a rate of about 15 per solar cycle. The largest GLE on record is the famous 1956 event [1] during which radiation levels near sea level increased by as much as 47 times in some regions. Several additional giant GLE were recorded in the pre-neutron monitor era by ionization chambers [2,3], but until this year no events in the giant GLE class (characterized by an increase of, say, 5 times or more in the sea level neutron rate at some location) had been observed since 1956. It is important to recognize the extremely large fluctuations in magnitude that solar particle events display when planning for radiation hazard mitigation in future human missions into deep space.

2. The Return of Giant GLE

Over a 6-minute span on January 20, 2005, the neutron rate at the sea level station of McMurdo, Antarctica increased by a factor of 30, while the rate at the high-altitude (2820 m) station of South Pole increased by a factor of 56. As shown in Figure 1, other stations observed an increase by only a factor of 3 or so. While large by recent historical standards, this does not approach the huge increase seen at McMurdo and Pole. Apparently this event was extremely anisotropic.

The size of the increase at McMurdo qualifies as the largest sea level increase since 1956; hence the January 20 event was the second largest GLE ever recorded. For comparison Table 1 lists the factor increase measured at some of the stations that were taking data during the 1956 event. The increase measured at South Pole may be the largest ever recorded by a neutron monitor. However, this distinction is owing largely to South Pole's unique location that is both high latitude and high altitude. Corrected to sea level, the South Pole increase over the Galactic background would have been "only" a factor of ~23.6.

29th International Cosmic Ray Conference Pune (2005) 00, 101-104

Observation of Neutron and Gamma Ray Emission from the October 28, 2003 Solar Flare

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Recently we published an analysis [1] of the response of the Tsumeb neutron monitor to the large solar flare of October 28, 2003. We concluded that the flare produced neutrons over an extended interval of approximately seven minutes. Gamma-rays observed from the SAMPEX spacecraft now confirm the extremely long duration of energetic emission from this event. Both POLAR and SAMPEX may have detected protons resulting from the decay of neutrons emitted by this flare. We use these data to determine the energy spectrum of neutrons emitted by the flare, and to further refine our calculation of the time structure of the emission. We compare the emission time structure of the neutrons and gamma-rays with available optical data, and with the injection profile of the GeV interplanetary protons in an attempt to identify the source region of this energetic radiation.

Acknowledgements

This work was supported in part by the U.S. National Science Foundation under grant ATM-0000315, by the Thailand Research Fund, and by the Rachadapisek Sompoj Fund of Chulalongkorn University.

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TI: Trapping, Diffusive Escape and Transport of Field Lines in Two-Component Magnetic Turbulence

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AB: The two-component model of magnetic turbulence, a reasonable model for turbulent magnetic field in interplanetary space, consists of slab and two-dimensional (2D) fluctuations. Field lines can be trapped within magnetic islands due to the topology of 2D turbulence while the slab turbulence contributes to escape and field line random walk. Therefore, the field lines in the two-component model can be both trapped and diffusive. Here we perform numerical simulations to examine trapping within 2D islands when field lines initially are located near 2D O-points or X-points until they escape and become diffusive. The results show that diffusion of field lines starting near O-points systematically changes, with a delay at the beginning and then approaching the 2D+slab turbulent diffusion rate at long distance. In contrast, field lines starting near X-points spread rapidly at the 2D+slab rate from the beginning. To have a better understanding of the mechanism of trapping and escape, we also model a single 2D island. We find that a strong 2D field can suppress the random walk of field lines due to the slab component. The simulations show that field lines starting deeply inside the island initially diffuse in radius but at a rate lower than when they are outside the

2D island; this is theoretically explained by applying a quasi-linear approach. In 2D+slab turbulence, sharp boundaries of trapping occur at intermediate distance. These boundaries can be empirically defined as trajectories of 2D turbulence where the appropriately averaged 2D field is a local maximum. Furthermore, we numerically measure the trapping length and show how it changes with various parameters. This study explains the underlying causes of inhomogeneity and sharp gradients in solar energetic particles from impulsive solar flares. This work was supported by US National Science Foundation grant ATM 0105254 and Thailand Research Fund.

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