The Astrophysical Journal, 682: L129–L132, 2008 August 1

EFFECT OF FLUX TUBES IN THE SOLAR WIND ON THE DIFFUSION OF ENERGETIC PARTICLES

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Received 2008 April 17; accepted 2008 June 20; published 2008 July 3

ABSTRACT

Current sheets are common structures in the solar wind and possibly the boundaries of individual flux tubes. Observations show that magnetic field directions often change abruptly upon crossing these structures. The presence of these structures introduces a new source of solar wind turbulence intermittency and can affect the transport of energetic particles. Previous studies of energetic-particle transport in the solar wind often assume a uniform large-scale background magnetic field, with a turbulent field superposed. With the existence of flux tubes in the solar wind, this picture needs to be changed. In this Letter, we study the effects of flux tubes on the transport of energetic particles in the solar wind. We construct a model turbulence of the solar wind by including explicitly flux-tube-like structures. In our model, the solar wind is composed of many individual cells with a local uniform mean magnetic field chosen randomly. The turbulence in each cell is modeled by either a slab and/or 2D type. We then calculate numerically the particle diffusion coefficients by following single particle trajectories. Our results show that flux tubes in the solar wind can lead to stronger scatterings of particles in directions both parallel and perpendicular to the large-scale background magnetic field. In particular, a true diffusion in the large-scale perpendicular direction (with respect to B_0) is obtained even when the local *intrinsic* turbulence in individual cells is of pure slab type.

Subject headings: diffusion — interplanetary medium — magnetic fields — scattering — solar wind — turbulence

Transport of energetic particles in the heliosphere is a central topic of space plasma physics. The classical quasi-linear theory (QLT) of charged-particle scattering by magnetic turbulence (Jokipii 1966) assumes charged particles' gyrocenters following magnetic field lines and that perpendicular diffusion and parallel diffusion can be calculated separately. QLT has been the foundation for us to understand cosmic-ray transport ever since it was developed. Later, to address the fact that the observed parallel scattering is often smaller than the result from QLT (Palmer 1982), Bieber et al. (1994) suggested that by using slab+2D composite turbulence model, QLT can describe parallel diffusion well with the assumption that 2D turbulence makes little contribution to the parallel transport. However, Qin et al. (2006) demonstrated that a finite parallel diffusion coefficient can be obtained for pure 2D turbulence in numerical simulations, and Qin et al. (2002a) also showed that parallel diffusion coefficients from numerical simulations are lower than QLT results for low-energy particles.

The perpendicular diffusion of charged particles has been a difficult problem for a very long time. The enhanced access of charged particles to widely disparate latitudes in the heliosphere (Maclennan et al. 2001) seems to suggest an enhanced transverse diffusion. On the other hand, the persistence of sharp dropouts in many solar energetic particle (SEP) events (Mazur et al. 2000) can be explained by a small transverse diffusion coefficient. Field line random walk (FLRW) is a perpendicular-transport theory based on the Jokipii (1966) QLT, by assuming charged particles' gyrocenters following magnetic field lines and that perpendicular diffusion and parallel diffusion can be calculated separately. However, FLRW usually does not agree with numerical simulations for low-energy particle transport (Giacalone & Jokipii 1999; Mace et al. 2000). In addition, it is possible that the motion of energetic particles in the perpendicular direction is not diffusive. Indeed, if the parallel motion of a particle is such that before and after a reversal due to a parallel scattering the field lines sampled by the gyromotion are the same or very similar (Urch 1977; Kóta & Jokipii 2000; Qin et al. 2002b), then the behavior of particles in the perpendicular direction is subdiffusive. However, if the field lines sampled by the particles' gyromotion have sufficient transverse structure, perpendicular diffusion is recovered at a level lower than that expected by FLRW. In order to address the nonlinear effect of particles' transport, Matthaeus et al. (2003) and Zank et al. (2004) presented a theory (NLGC) of the perpendicular diffusion of charged particles using the Taylor-Green-Kubo (TGK) formulation (e.g., Kubo 1957), including the influence of parallel scattering and dynamical turbulence. Based on QLT with nonlinear extensions that consider the motion of the guiding centers perpendicular to the background field, Shalchi et al. (2004) presented the WNLT theory to calculate perpendicular and parallel diffusion coefficients simultaneously. Following those approximations as in the derivation of NLGC, Qin (2007) developed another nonlinear theory for parallel diffusion, so the NLGC is extended (NLGC-E) to describe both parallel and perpendicular diffusion at the same time.

Note that in the discussion of particles' diffusion mechanism above, a uniform large-scale background magnetic field with a superposed turbulent field is assumed. To study the effect of the different length scales and timescales, Webb et al. (2003) studied transport and acceleration of energetic charged particles in quasi-periodic, fluid velocity structures with multiple-scale perturbation methods. In Webb et al. (2003) the turbulent diffusion coefficients are obtained by ensemble averaging over random and periodic structures with small correlation lengths.

Using *ACE* data, Borovsky (2006) recently suggested that flux-tube-like structures may exist in the solar wind. In this scenario, the turbulence in the solar wind is confined in individual flux tubes and these flux tubes move independently of each other. Across the boundary of these flux tubes, the mag-

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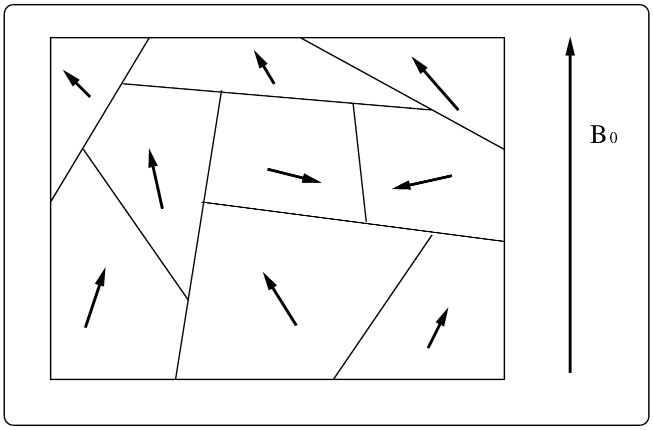

FIG. 1.—Cartoon showing our cell model of the solar wind. The background magnetic field is denoted by B_0. In each cell, a local background $B_0^{\rm local}$ is represented by the arrow, whose direction differs from B_0. For the purpose of illustration, this cartoon is in 2D. Our "cell model" is, however, a 3D model. See text for details.

netic field (direction) changes quickly and significantly from one side to another. The idea of plasma in the solar wind being bundled in a "spaghetti-like" structure is not new. It was first proposed some 40 years ago as an attempt to explain the modulation of cosmic rays (Bartley et al. 1966; McCracken & Ness 1966). The inadequacy of this model was discussed by Burlaga (1969) who showed the existence of numerous directional discontinuities in the solar wind and that the magnetic field direction between discontinuities is not uniform. Later the model was adopted by Mariani et al. (1973) to explain the observed variations of the occurrence rate of discontinuities in the interplanetary magnetic field. Recently, in studying and characterizing the solar wind intermittency in the inner heliosphere, the idea of a spaghetti-like structure has been revived (Bruno et al. 2001, 2004; Chang et al. 2004). In particular, Bruno et al. (2001) noted that the existence of flux tubes in the solar wind will complicate the study of solar wind intermittency and lead to a modification of the present-day data analysis. Extending the work of Borovsky (2006), Li developed a new data analysis method (Li 2007, 2008) to identify flux-tube-like structures in the solar wind plasma. They showed that "magnetic walls" are very common at 1 AU and spacecraft such as *ACE* and/or *Wind* may cross flux tubes with a rate of several times per hour. At this rate, it is necessary to consider the effect of these flux tubes on the transport of energetic particles.

In this Letter we investigate the effects of flux tubes on the transport of energetic particles. We construct a model turbulence of the solar wind which includes explicitly flux-tube-like structures. We then calculate numerically the parallel and perpendicular diffusion coefficients by following test particles' trajectories. Our simulations show that the presence of flux tubes in the solar wind can cause stronger scattering in directions both perpendicular and parallel to the large-scale mean background magnetic field $\boldsymbol{B}_0$. When there are flux tubes present, even if the turbulence in individual cells is assumed to be *intrinsically* of pure slab type, strong scatterings along the perpendicular direction of the large-scale $\boldsymbol{B}_0$ will develop. This leads to a true diffusion in the perpendicular direction, in contrast to a subdiffusion in a pure slab geometry.

We construct a so-called cell model of the solar wind turbulence. In this model the solar wind is treated as composed of small cells with random size. Adjacent cells are separated by magnetic walls. In every individual cell, the magnetic field consists of a uniform mean magnetic field $B_0^{\rm local}$ and a turbulent magnetic field δB. The direction of $B_0^{\rm local}$ may differ from the direction of the underlying large-scale background field $\boldsymbol{B}_0$ but having the same magnitude as $\boldsymbol{B}_0$. The turbulent magnetic field is given by, for example, that of a slab model and/or a 2D turbulence model. The assumption of an equal magnitude of $B_0^{\rm local}$ in different cells is for simplicity since observations do show that the magnitude of magnetic field may change across a rotational discontinuity if the underlying plasma is anisotropic (Hudson 1970). We further ignore the thickness of magnetic walls. Consequently the change of magnetic field direction is modeled as sharp kinks. We note that the normal component of the magnetic field B_n in our model is not continuous across the boundary. This noncontinuous B_n is due to our assumption of a zero thickness of the magnetic wall, which leads to a kinked magnetic field. In reality, the magnetic wall has a certain thickness (~8–10 s; see Li 2008) and currents can exist inside the wall. So the direction of the magnetic field changes gradually inside the wall. Modeling sudden changes of magnetic field direction by kinks has been also adopted by Webb & Quenby (1974), who studied how kinks can affect $\kappa_{||}$ by integrating over particle trajectories. The model used in Webb & Quenby (1974), however, has many limitations as it assumes a series of *equally* spaced field discontinuities with *equal* angular displacements, constant $|B|$, and *oppositely directed* successive displacements.

Our cell model is a 3D model. We assume the size of the solar wind to be modeled occupies a space (denoted as M below) of $100\lambda \times 100\lambda \times 100\lambda$, where λ is the local *intrinsic* turbulence parallel scale. We impose periodic boundary conditions at all six boundary planes. We then divide M into $64^3 = 262{,}144$ convex polyhedron (cells) randomly. The average length scale of the cell $l_{\rm cell}$ is $100\lambda/64$. Taking $\lambda = 0.02$ AU as a typical value in the solar wind near 1 AU, we obtain $l_{\rm cell} \sim 0.03$ AU. Figure 1 is a 2D cartoon to illustrate our cell model. The large-scale background magnetic field is denoted by the arrow on the right. In each cell, the local $\boldsymbol{B}_0^{\rm local}$s are shown as the small arrows, whose directions differ from $\boldsymbol{B}_0$. Note that all lengths are scaled to the local intrinsic turbulence scale λ. In each cell, we assume the background magnetic field $\boldsymbol{B}_0^{\rm local} = B_0\hat{z}'$. In choosing the direction $\hat{z}'$, we assume that the angle between $\hat{z}'$ and $\hat{z}$, $\alpha = \cos^{-1}(\hat{z}\cdot\hat{z}')$, obeys the distribution function

$$F(\alpha) = \frac{2}{\alpha_{\rm max}}\left(1 - \frac{\alpha}{\alpha_{\rm max}}\right), \qquad (1)$$

where $\alpha_{\rm max}$ is the maximum angle between $\hat{z}'$ and $\hat{z}$ and taken to be $\alpha_{\rm max} = (5/6)\pi$ in this work. This probability distribution has a maximum at $\hat{z}' = \hat{z}$ and decreases linearly to zero at $\alpha = \alpha_{\rm max}$. For clarity, we have used two sets of coordinate systems. The one without primes (x, y, z) denotes Cartesian coordinates with $\hat{z}$ parallel to $\boldsymbol{B}_0$, and the one with primes (x', y', z') denotes that with $\hat{z}'$ parallel to $\boldsymbol{B}_0$.

In each cell the total magnetic field $\boldsymbol{B}(\boldsymbol{x}') = \boldsymbol{B}_0^{\rm local} + \boldsymbol{b}(\boldsymbol{x}')$. Here $\boldsymbol{b}(\boldsymbol{x}')$ is a zero-average fluctuation and is assumed to be determined with a turbulence model consisting of a 1D slab component $\boldsymbol{b}^{\rm slab}(z')$ and a 2D component $\boldsymbol{b}^{\rm 2D}(x', y')$ (Matthaeus et al. 1990; Bieber et al. 1996). We refer the model turbulence confined in each cell as the local *intrinsic* turbulence, and describe it using numerical methods similar to Qin et al. (2002a, 2002b). We vary the ratio $E^{\rm slab} : E^{\rm total} \equiv E^{\rm slab} : (E^{\rm slab} + E^{\rm 2D})$ from 0 to 1, to change the turbulence geometry from a pure

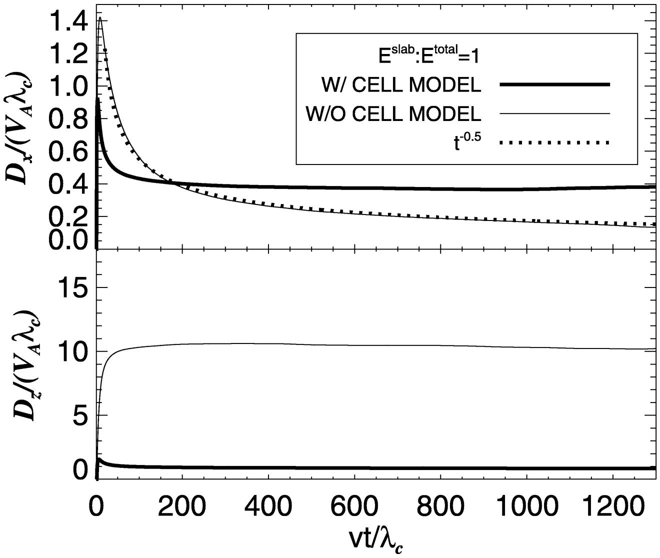

FIG. 2.—Running perpendicular diffusion (*top*) and running parallel diffusion (*bottom*). Thick lines indicate local intrinsic pure slab turbulence with the cell model. Thin lines indicate the same intrinsic turbulence without the cell model. The intrinsic turbulence with or without the cell model is pure slab with $r_L/\lambda_c = 0.098$ and $b/B_0 = 1.0$.

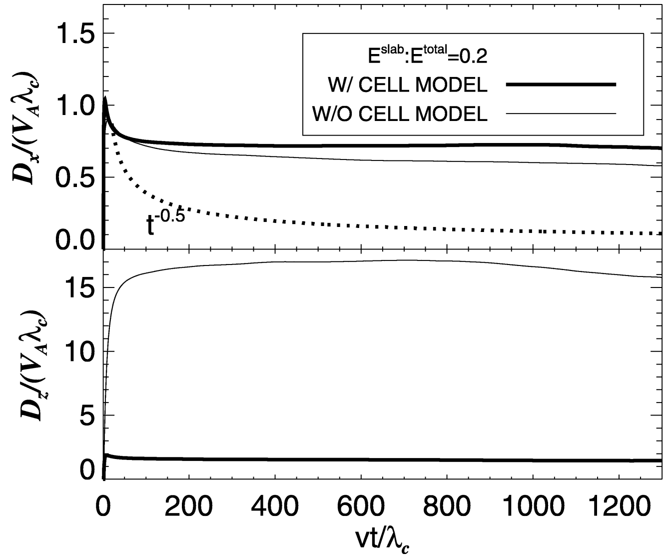

FIG. 3.—Running diffusion coefficients of test particle simulations vs. time. All conditions are the same as in Fig. 2 except that the intrinsic turbulence with or without the cell model is a composite model with $E_{\rm slab} : (E_{\rm slab} + E_{\rm 2D}) = 0.2$.

2D case to a pure slab case. In the following, to be in agreement with the existing literature, we suppress the primes (′) of the (x', y', z') when discussing the local *intrinsic* turbulence. For the slab component, we take a length of 10,000λ in the $\hat{z}$ direction and choose a total of $N_z = 2^{22}$ points. The slab spectral amplitude is chosen as $S_{xx}^{\rm slab}(k_\parallel) = C(\nu)\lambda\langle b_{\rm slab}^2\rangle(1 + k_\parallel^2\lambda^2)^{-\nu}$, where the parallel turbulence scale λ is of the order of parallel turbulence correlation length λ_c with $\lambda_c = 2\pi C(\nu)\lambda$, and $C(\nu) = (2\pi^{1/2})^{-1}\Gamma(\nu)/\Gamma(\nu - 1/2)$; $\Gamma(\cdots)$ is the Gamma function and the constant $\nu = 5/6$. For the 2D component, we assume a box with size 10λ × 10λ and a total of $N_x \times N_y$ points with $N_x = N_y = 4096$. The 2D spectrum is chosen as $S_{xx}^{\rm 2D}(k_\perp) = C(\nu)\lambda_x\langle b_{\rm 2D}^2\rangle(1 + k_\perp^2\lambda_x^2)^{-\nu}/(\pi k_\perp)$; here the perpendicular scale $\lambda_x = 0.1\lambda$ is of the order of perpendicular correlation length.

In our model, energetic particles are treated as test particles and their effects on the background plasma are neglected. We follow particles' trajectories numerically using a fourth-order adaptive-step Runge-Kutta method with a relative error control set to 10^{-9} (Qin et al. 2002a, 2002b). We calculate the running diffusion coefficients using the Kubo formula through

$$D_x(t) = \langle(\Delta x)^2\rangle/2t, \tag{2}$$

$$D_z(t) = \langle(\Delta z)^2\rangle/2t, \tag{3}$$

where the brackets $\langle\cdots\rangle$ indicate the ensemble average. We vary the ratio of $E^{\rm slab} : E^{\rm total} \equiv E^{\rm slab} : (E^{\rm slab} + E^{\rm 2D})$ to examine the effect of the local turbulence (slab or 2D) on both $D_x(t)$ and $D_z(t)$.

Figure 2 plots the perpendicular (*top panel*) and parallel (*bottom panel*) running diffusion coefficients when the local intrinsic turbulence is of pure slab type ($E^{\rm slab} : E^{\rm total} = 1$). The ratio of gyroradius to parallel turbulence correlation length is taken to be $r_L/\lambda_c = 0.097$ and the turbulence level is $b/B_0 = 1$. The thick lines are for the cell model, with flux tubes in the solar wind, and the thin lines assume no flux tubes in the solar wind. In addition, a dotted line proportional to $t^{-1/2}$ is shown in the top panel of Figure 2. Consider first the running parallel diffusion coefficients in Figure 2 (*bottom panel*). At very short timescales, both the thin line (no cell structure) and the thick line (with cell structure) increase very quickly. This corresponds to the initial free-streaming period. Then the D_zs reach their maxima around $t \sim \lambda_\parallel/v$ and remain almost constant afterward, implying a diffusion in the $\hat{z}$ direction. Note that the value of D_z for the case of no cell structure is about 10 times larger than that for the case of having a cell structure. This suggests that the presence of cells greatly enhances the scatterings along the $\hat{z}$ direction. In comparison, the running perpendicular diffusion coefficients for the case of no cell structure and the case of having cell structure are very different. When there is no cell structure, D_x first increases, reaching a maximum very quickly $t < 20\lambda_c/v$, and then decreases and follows the dotted $t^{-1/2}$ line closely, yielding the well-known subdiffusion (Urch 1977; Kóta & Jokipii 2000; Qin et al. 2002b). This decrease is because most particles have by now traveled several parallel mean free paths so that in the parallel direction diffusion has set in. In stark contrast, when there is cell structure, the running diffusion coefficient D_x no longer follows $t^{-1/2}$ at $t > 20\lambda_c/v$. Instead, D_x at later times decreases and settles into a constant value, suggesting a diffusion process in the perpendicular direction, which we refer to as the "second diffusion."

We next change the local intrinsic turbulence in individual cells from pure slab to composite turbulence (slab+2D). The results are shown in Figure 3. We take $E^{\rm slab} : E^{\rm total} = 0.2$ in describing the local *intrinsic* turbulence, and keep all other parameters the same as in Figure 2. Again the thick lines are for the cell model of the solar wind turbulence and the thin lines are for the conventional solar wind turbulence. Comparing to Figure 2, we note first that the motion of energetic particles at late times is described by diffusion in both the (large scale) parallel direction and the (large scale) perpendicular direction. This is hardly a new result (see Qin et al. 2002a). In fact, to recover a diffusion in the perpendicular direction probably motivated the introduction of 2D turbulence. Second, we note that the presence of flux tubes in the solar wind seems to affect D_z more than D_x even when the intrinsic turbulence is more of 2D type. Indeed, at time $t \sim 1200\lambda_c/v$, we find D_x for the cell model is only about 15% larger, while D_z for the cell model is about 10 times smaller. This much smaller D_z in the cell model can also be seen in Figure 2, where the intrinsic turbulence is pure slab. Thus, from both Figure 2 and Figure 3, we can conclude that no matter what the intrinsic turbulence is, the presence of flux tubes in the solar wind can effectively decrease D_z.

We now discuss our results. In studying the transport of energetic particles in the solar wind, it has been assumed that the magnetic field is composed of a uniform large-scale background B_0 with a superposed intrinsic δB. However, such a scenario has been recently shown (Bruno et al. 2004; Borovsky 2006; Li 2007, 2008) incomplete. In particular, the study of (Li 2007, 2008) found that current-sheet-like structures are common in the solar wind and likely originated from the Sun. These current sheets separate solar wind plasmas into individual flux tubes and the magnetic field directions change significantly from one flux tube to the next.

In this Letter, we investigate the effects of flux tubes in the solar wind on the transport of energetic particles. We construct a cell model of the solar wind turbulence and obtain the diffusion coefficient of energetic particles. Our results show that when flux tubes are present, a large-scale perpendicular diffusion will emerge even when the local intrinsic turbulence in individual flux tubes is of pure slab type. This is an important finding as previous studies have shown that the motion of energetic particles in the large-scale perpendicular direction is of subdiffusion when the underlying turbulence is of pure slab geometry. Thus to account for a diffusion in the perpendicular diffusion, a 2D composite turbulence was forced to be introduced. However, our results here indicate that a 2D composite turbulence is not necessary for a large-scale perpendicular diffusion; providing there are flux-tube-like structures in the solar wind, a turbulence of pure slab geometry can naturally lead to a large-scale perpendicular diffusion. Thus if one accept the existence of flux tubes in the solar wind, then a true diffusion of energetic particle is always established, whether or not the transverse structure of the local intrinsic turbulence is present. This can be qualitatively understood as the following: in our cell model, particle motion inside each cell (flux tube) is controlled by the local background $\boldsymbol{B}_0^{\rm local}$ and the superposed intrinsic turbulence; therefore they tend to move along local $\boldsymbol{B}_0^{\rm local}$ with some scatterings. On crossing the flux tube boundaries, however, particles would "feel" a sudden change of magnetic field direction, whose effect is equivalent to some additional scattering in both parallel and perpendicular directions. Therefore, even with a pure slab intrinsic turbulence, the cell model will lead to a large-scale perpendicular "secondary diffusion" over the otherwise subdiffusion. Furthermore, both Figures 2 and 3 show that the presence of flux-tube-like structures tends to highly enhance the scatterings in the parallel direction. This raises the issue of understanding the observed mean free paths of cosmic rays, e.g., the SEP "too small" mean free paths problem (Palmer 1982; Bieber et al. 1994), as these works all ignore the presence of flux-tube-like structures in the solar wind and are therefore incomplete. Besides enhanced scatterings along the large-scale background B_0, our results also show enhancement of scatterings along the large-scale perpendicular direction. This may provide a natural way to explain the observed SEP's transverse diffusion (e.g., Maclennan et al. 2001).

Finally, we note that our cell model is only a crude approximation of the solar wind MHD turbulence. In reality, the solar wind is far more complicated and a hierarchical cell model, analogous to the eddy cascade model of turbulence, would be necessary. As such, quantitative conclusions from our model may not apply to the solar wind. However, qualitatively, that there exists flux tubes in the solar wind and these flux tubes can lead to large-scale perpendicular diffusion of energetic particles is fairly robust. Therefore, a proper understanding of energetic-particle transport in the solar wind should include the effects of flux tubes.

This work was supported partly by grants NNSFC 40621003, 40674095, and 40523006 for G. Q., and NASA grants NNG05GM62G and NNX06AC21G for G. L. G. L. acknowledges discussions with Yan Wang, and the authors would like to thank the referee for useful suggestions.

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