THE TRANSPORT OF ENERGETIC PARTICLES AND COSMIC RAYS IN THE HELIOSPHERE

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ABSTRACT

We discuss recent observations of energetic particles and cosmic rays lending insight into how these particles are influenced by the interplanetary magnetic field and what can be learned about the field itself by using the energetic particles as probes. Two recent observations on which we focus attention are those by Ulysses at high heliographic latitudes and those by the Advanced Composition Explorer of impulsive solar flare events. The Ulysses observations of low-rigidity energetic particles at high latitudes associated with corotating interaction regions at lower latitudes are consistent with propagation in a stochastic field superimposed on a Parker spiral. These observations indicate that the particles undergo a significant cross-field diffusion. More-recent observation of energetic particles from impulsive solar flare events show structure on a fine scale which seems also to reflect the field-line meandering. Large small-scale gradients normal to the local magnetic field are shown to be completely consistent with significant cross-field diffusion on larger time scales.

INTRODUCTION

The study of the transport of energetic charged particles in a specified irregular magnetic field has a long history. The current paradigm is to consider the magnetic field to be the combination of a causal field (which is taken to be the average field) and a stochastic (turbulent) field, which has zero mean and which is treated statistically. The charged-particle motions in the causal field are generally regarded as well known and consist of the usual gyromotion and superposed large-scale drifts. The turbulent fluctuations scatter the particles in pitch angle and cause diffusive motion. Treatments based on this paradigm began in the 1960's (e.g. Jokipii, 1966) and continue to the present (e.g. le Roux et al., 1999). It is generally held that the motion *normal* to the average or causal field is poorly understood. Recent observational advances, whcih we discuss below, have made it possible to study the perpendicular motion in a new way.

Observations of energetic particles and galactic cosmic rays from the Ulysses spacecraft, which went to high heliographic latitudes, have made it possible to study the transport normal to the nominal Parker spiral magnetic field, which has no latitudinal component. The observations have revealed that these particles propagate in heliographic latitude relatively easily. Corotating interaction regions (CIRs) form in the interaction region of high and low speed solar wind near the heliographic equator. Galactic cosmic rays show co-rotating variations, evidently produced by CIRs at low latitudes, up to the highest latitudes reached by Ulysses (McKibben et al., 1995), where there was no evidence of co-rotating variations in the solar wind or magnetic field. When Ulysses was at high latitudes, these regions were confined to within some 40 degrees of the equatorial plane of the Sun, and are unlikely to expand much beyond this range as they move out to the more distant heliosphere. Also of considerable interest was the fact that very low energy electrons ($\approx$50 keV) and sub MeV protons, which are known to be accelerated at the shock waves which surround CIRs, are observed up to the highest latitudes viewed by Ulysses, more than 80 degrees (e.g. Simnett and Roelof, 1995). Because of their low rigidities, these particles might be expected to have small transport normal to the magnetic field.

These observations are particularly interesting when one considers the standard form for the heliospheric magnetic field, which was shown by Parker (1958) to be an Archimedes spiral pattern, lying on cones of constant latitude. The field is assumed to be attached to the rotating Sun, and carried radially outward with the solar wind. In this model, then, there needs to be extensive cross-field propagation, which would not necessarily have been expected, particularly for the low energy particles. Here it is important to remember that the fluctuating, or random, part of the field has long been known to have a latitudinal component.

THE HELIOSPHERIC MAGNETIC FIELD

The heliospheric magnetic field influences the motion of charged particles, and hence is a natural starting point to interpreting spacecraft observations and understanding the underlying physics. The energy density of this field is small compared to the solar wind ram pressure. Hence, the field does not play an important dynamical role and its structure is determined by the manifold plasma processes in the solar atmosphere and solar wind. In its simplest form, the heliospheric magnetic field is a Parker spiral. The radial component falls off as r^{-2} and the azimuthal component as r^{-1}. However, it has become increasingly recognized that in order to understand various spacecraft observations of energetic charged particles the field must be somewhat more complicated than the simple picture.

To fully understand the nature of the heliospheric magnetic field in interplanetary space, we must understand its origin at the Sun. The field consists of both a simple Parker spiral upon which is superimposed a component caused by stochastic processes occurring at the Sun, and also, perhaps, another causal component due to the differential rotation of the Sun (Fisk, 1996). Jokipii and Parker (1969) and more recently Jokipii et al. (1995) related the braiding to observed supergranule motions in the photosphere, where the expected diffusion of field lines on the Sun should lead to considerable intertwining. This is illustrated in Figures 1 and 2.

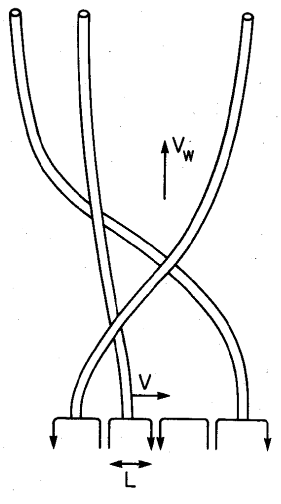

Fig. 1. Schematic illustration of the introduction of field braiding near the Sun (Jokipii and Parker, 1969). The basic picture remains much the same if there is significant reconnection near the Sun, as is presently thought.

Figure 2 shows magnetic field lines for a quantitative model developed by Giacalone (2001) to study the propagation of CIR-associated particles. Shown are two different field representations: the combination of a Parker spiral plus a fluctuating component (left and middle plots) determined by random motions at the source surface, and a Parker spiral (right plots). The field lines originate at 30°

(polar angle) and show significant latitudinal excursions compared to the case of no fluctuations. The field line diffusion depends on the diffusion associated with the random motions of the foot points. The diffusion coefficient associated with these motions is given by $\kappa_{fp} = (1/3)V_g^2 T_c$, where V_g and T_c are the characteristic speed and time associated with the supergranulation (e.g., Jokipii et al., 1995). The latitudinal motions of the field lines scale with T_c as can be seen in Figure 2.

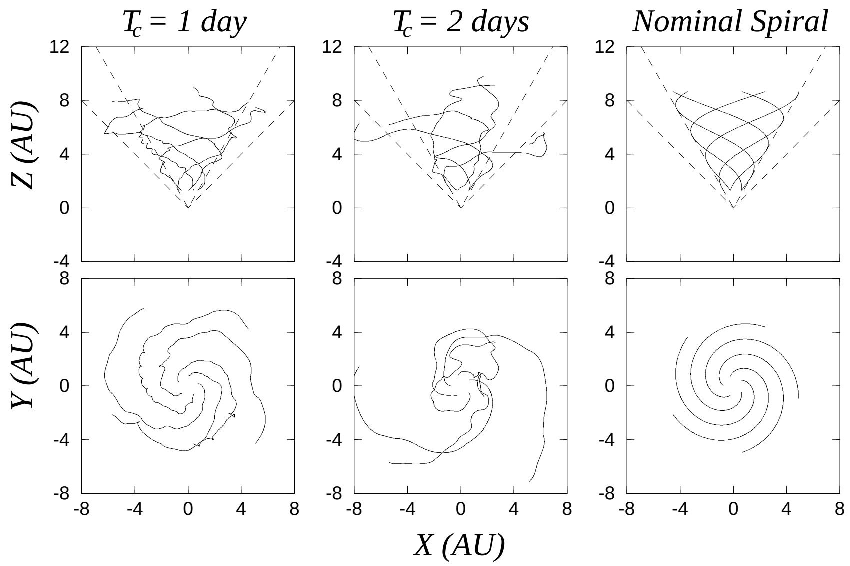

Fig. 2. Illustration of the magnetic field lines as projected out into the heliosphere (Giacalone, 1999). The upper and lower right panels show two orthogonal views of the Parker spiral and the left four panels show corresponding views of the field with the random walk or braiding included. The results assume a supergranulation rms velocity of 0.6 kms^{-1}.

SOLAR-ENERGETIC PARTICLES vs. GLOBAL COSMIC-RAY DIFFUSION

CIR-Associated Particles at High Heliographic Latitudes

Observations from the Ulysses spacecraft at high heliographic latitudes have revealed that galactic and anomalous cosmic rays are affected by the lower-latitude CIRs. Moreover, lower-energy ions and electrons accelerated at CIRs revealed co-rotating effects up to high latitudes where there were no apparent effects of the CIRs on the magnetic field or plasma (Simnett et al. 1995). One explanation for this involves significant cross-field diffusion, while another involves direct latitudinal magnetic connection via a non-Parker magnetic field (Fisk and Jokipii, 1999).

Figure 3 shows the results from two models. The left plots (upper and lower left panels) shows results from a model by Giacalone (2001) in which the trajectories of test particles were integrated numerically in synthesized electric and magnetic fields. The heliospheric magnetic field was determined by the random motions of magnetic foot points associated with solar supergranulation. We found that the resulting long-wavelength magnetic fluctuations lead to significant latitudinal field line diffusion which simultaneously leads to significant latitudinal transport of CIR-associated energetic particles.

The right plots of Figure 3 show results from the three-dimensional transport model by Kóta and Jokipii (1998). This quantitative numerical model was used to simulate the effects of CIRs and they found that values of the ratio $\kappa_\perp/\kappa_\parallel$ of the order 0.03-0.1 (the same order as that used in the modulation of galactic cosmic rays discussed above) were needed to account for the Ulysses observations.

Impulsive Solar Flare Events

Over the past decade or so, it has been established that there are at least two quite distinct kinds of solar-energetic particle events, impulsive and gradual, with quite different characteristics (see, e.g., Reames et al., 1997, for a discussion and references to the literature). Impulsive events are associate with large changes in composition even between nearby isotopes, which appear to require the action of resonant wave-particle interactions in the corona. The energetic particles in gradual events, on the other hand, appear to be accelerated by shock waves in interplanetary space.

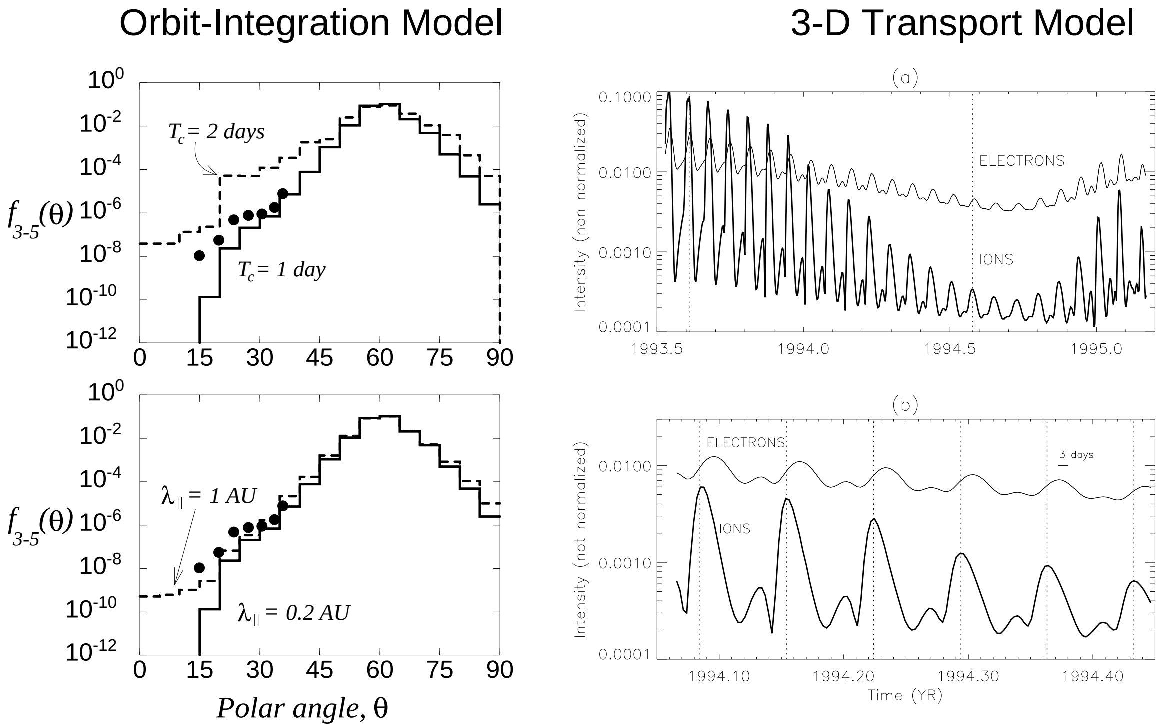

Fig. 3. (lower and upper left) Numerical simulations showing the latitudinal variation of CIR-associated particles. T_c is the characteristic time of the model supergranulation and $\lambda_{||}$ is the parallel mean-free path. Solid circles are Ulysses data (1-3-MeV protons) from Sanderson et al. (1995). (lower and upper right) Intensity of cosmic rays as simulated by the Arizona model along the path of Ulysses, at two different time resolutions. Standard transport parameters were used. The wind and magnetic field had no structure above about 30^o latitude. The vertical dotted lines in the lower right panel are 26-day time separations.

Recent observations by the ACE spacecraft show fine-scale variations in the intensity profiles of energetic particles associated with impulsive solar flares (Mazur et al., 2000). These are consistent with the passage of alternatively filled and empty tubes of energetic-particle flux by the spacecraft. The magnetic field lines, to which these particles adhere closely, are mixed and braided on spatial scales that are much larger than the gyroradii of the particles. Similar observations have also been discussed Roelof et al. (1983).

Giacalone et al. (2000) recently developed a model to interpret the recent observations of energetic particles associated with impulsive solar flares. The model is the same (except for the source) as the one described by Giacalone (2001) (also see Figure 3) which was used to study the propagation of CIR-associated particles to high heliographic latitudes. For the flare model, the source is impulsive and the spatial extent is much smaller (on the order of the characteristic size of supergranulation). Figure 4 and 5 display results from the flare model.

Shown in Figure 4 are the positions of all particles projected onto the solar-equatorial plane at two different times after the onset of the flare (as indicated). Some structures which correspond to filled and empty flux tubes are clearly evident. Shown in Figure 5 are plots of the arrival time versus energy for the particles observed by a spacecraft placed at 1 AU for two simulations with different source sizes (as indicated). For the case of a small source size, there are distinct dropouts in particle intensity but are nearly absent for the larger source. This explains why larger, or non-impulsive, events do not show the dropouts (Mazur et al., 2000).

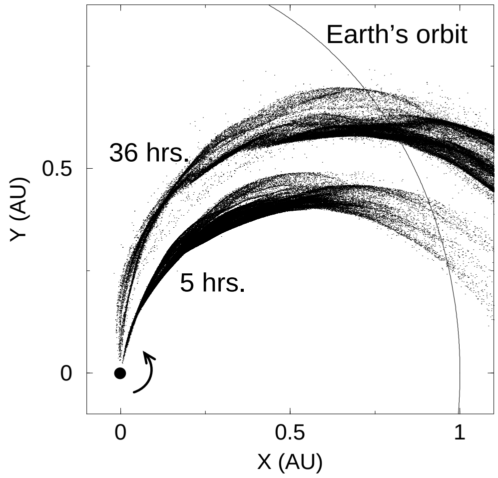

Fig. 4. Results from the flare model of Giacalone et al. (2000). Shown are the positions of the impulsive flare particles at two different times after injection.

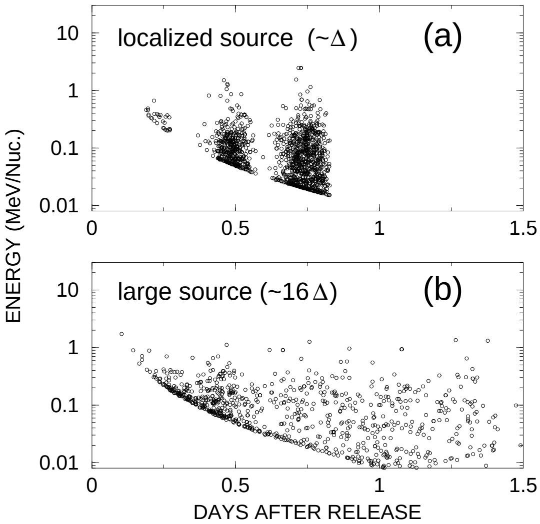

Fig. 5. Energy vs. time scatter plots of the particles detected by an arbitrarily placed spacecraft, corresponding to the flare simulations shown in Figure 4. The upper and lower panels are for different source sizes as indicated. The upper panel is for an event in which the particles were released over a small localized region which is on the order of the field coherence scale (same event as that shown in Figure 4). The lower panel (b) uses a much larger source region, on the order of several coherence scales.

CROSS-FIELD DIFFUSION

The observational and modeling studies discussed above provide insight into how charged particles move across a turbulent magnetic field. The importance of the collisionless transport of energetic particles and cosmic rays normal to the average magnetic field has become increasingly recognized. Unfortunately cross-field diffusion is not very well understood. Currently there is not a consensus value for the perpendicular diffusion coefficient, even in general order of magnitude, in many important situations. For example, it has been thought that the perpendicular transport of ≈ few hundred keV nuclei was small, but recent direct measurements suggest that it may be quite large (on the order of the parallel diffusion coefficient) in certain circumstances (e.g. Dwyer et al, 1997).

Since charged particles move approximately along magnetic lines of force, perpendicular transport is composed of two parts. The first part is the transfer of particles from one field line to the next (across the local magnetic field), resulting from of either scattering or drift. The second part is that the field lines themselves are braided or mixed in the transverse direction, resulting in particles moving in the direction normal to the average magnetic-field direction. This field-line random walk contribution has been known for more than thirty years (Jokipii, 1966; Jokipii and Parker, 1969), and a number of papers have considered it (e.g. Forman, et al., 1974; Forman, 1977; Bieber and Matthaeus, 1997), but there is as yet no general consensus concerning its magnitude.

Figure 6 shows the numerical simulation results of Giacalone and Jokipii (1999) in which the trajectories of charged particles were numerically integrated in pre-specified, three-dimensional, random magnetic turbulence. $\kappa_\perp$ and $\kappa_{||}$ are the perpendicular and parallel diffusion coefficients, respectively. Plotted are $\kappa_\perp$ and the ratio $\kappa_\perp/\kappa_{||}$ as a function of rigidity. The solid circles are for an isotropic turbulence spectrum and the open circles uses a composite spectrum consisting of 20% slab turbulence and 80% two-dimensional turbulence (c.f. Bieber et al., 1996). These simulations show that the ratio $\kappa_\perp/\kappa_{||} \simeq 0.025$ for 1-1000 MeV protons which is of the same general magnitude as values used by Kóta and Jokipii (1998).

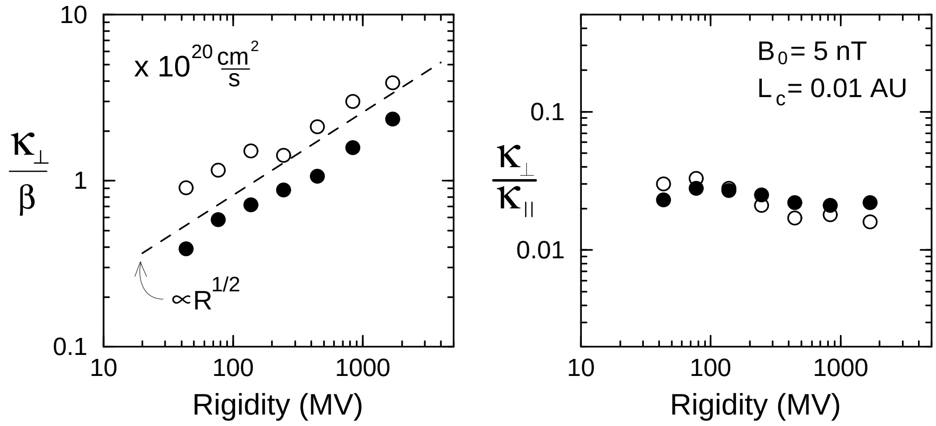

Fig. 6. (left) Perpendicular transport coefficient (divided by $\beta = v/c$) and (right) ratio of perpendicular to parallel transport coefficient as a function of particle rigidity based on the numerical simulations of Giacalone and Jokipii (1999). B_0 is the mean field strength and L_c is the correlation length.

The observations and modeling of impulsive solar flare events provides additional information on cross-field diffusion. The existence of the large, cross-field gradients in the intensity of the solar energetic particles would seem to be evidence for a small rate of perpendicular diffusion. However, the parameters of the model magnetic field used in the numerical simulations of impulsive solar flares discussed above are the same as those used in the CIR simulations. Consequently, the models suggest that the observed large cross-field gradients (flux "dropouts"), are consistent with the simultaneous large-scale diffusion.

Figure 7 illustrates our interpretation. For the case of a localized source, it takes many scattering times for the particles to diffuse through a region large compared to the correlation length of the turbulence. If the time of the observation is on the order of the particle scattering time, the particles are closely bunched to the magnetic field lines in which they start (left panel). We note that scattering is required in order for particles to be able to move off of field lines. Thus, for times larger than the scattering time, the gradients will be much smaller (as we expect, for example, in the outer heliosphere).

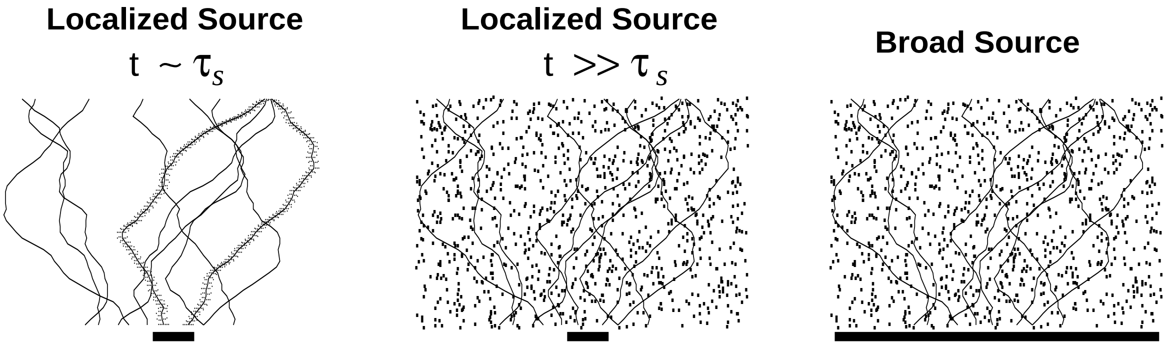

Fig. 7. Cartoon sketch illustrating how the same magnetic field can have simultaneously large localized gradients (far left panel), and significant particle diffusion (middle and right panels). τ_s is the particle scattering time (the mean-free path measured along the magnetic lines of force divided by the particle speed) and t is the time of the observation.

For the problem of impulsive solar flares, the time for the particles to propagate to Earth is on the order of the scattering time. For these short times, the particles can only move normal to the magnetic field via classical diffusion given by

$$\frac{\kappa_\perp}{\kappa_\parallel} = \frac{1}{1+(\omega_c \tau_s)^2} \tag{1}$$

where ω_c is the particle gyrofrequency in the magnetic field.

After a time t the characteristic scale associated with the diffusion off of the field lines is $T_c = L_d/V_w$, where V_w is the solar wind speed. Using (1) and assuming that the scattering time is much larger than the particle gyroperiod, we find

$$T_c = \left(\frac{4}{3}\right)^{1/2} \frac{v}{V_w} \left(\frac{t}{\tau_s}\right)^{1/2} \omega_c^{-1} \tag{2}$$

where v is the particle speed.

For 1-MeV/N particles moving in a 5 nT field and a wind speed of 500 kms^{-1}, we find $T_c \simeq 1.1(t/\tau_s)^{1/2}$ minutes. Since the time of arrival at 1 AU of impulsive solar flare particles is on the order of the scattering time, T_c is on the order of a minute or so. This is consistent with ACE observations (Mazur et al., 2000).

SUMMARY AND CONCLUSIONS

Recent observations and developments in our understanding of transport in a stochastic magnetic field have provided new insights into the transport of solar-flare and cosmic-ray particles. We can now incorporate the observations of large, small-scale gradients in the particle intensity normal to the local magnetic field *and* the requirements of significant perpendicular transport into one comprehensive model of transport in a field having both a stochastic and a causal component. Large-scale observations of galactic and anomalous cosmic rays and small-scale solar particle observations fit into one magnetic field model.

In the new picture, transient gradients occur during the first few scattering times after particles are injected into a region small compared with the coherence scale of the magnetic field. The particles, in this short time, remain anisotropic and do not have time to shift to new field lines. Because of the random walk of the flux tubes, a spacecraft such as ACE sees a rapidly fluctuating intensity as alternately filled and empty flux tubes are convected past the spacecraft. Particles injected in a region several coherence scales in size are much more uniformly distributed, as all flux tubes are filled. After the particles propagate for several scattering times, they become diffusive and can move normal to the field. For the parameters in the solar wind near 1 AU, the ratio $\kappa_\perp/\kappa_\|$ for large-scale motion, is of the order of a few percent to 10 percent. This seems to account well for both the Ulysses and ACE observations. This new understanding makes it plausible that the transport of solar and galactic cosmic rays may be explained with the same transport parameters. This will be the subject of future work.

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