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Diffusive particle transport in heliomagnetic fields with organized latitudinal components

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Abstract. We discuss the potential role the meridional component of the large-scale heliospheric magnetic field (HMF) might play in the transport of cosmic rays. The standard Archimedean spiral lines of the steady, large-scale HMF has no latitudinal component. Hence latitudinal transport of particles may occur only through particle drifts and cross-field diffusion. Most of the numerical works developed so far were built on and taking advantage of this presumption. Although the inclusion of an additional meridional field component is simple conceptually it still poses serious challenges to numerical models. The present work considers examples where organized latitudinal field is present. We address the Fisk field as the prime target of the present work. Also discussed are the meridional fields that inescapably emerge in connection with the reorganization of the global HMF as the tilt angle of the heliospheric current sheet (HCS) changes. Analytical approximations and numerical simulations are attempted. The presence of a small organized latitudinal field is important if cross-field diffusion ($\kappa_\perp$) is small. We present the results of a numerical code custom-designed for this specific purpose optimized for small $\kappa_\perp$.

1 Introduction

The first polar pass of Ulysses brought a number a remarkable discoveries. The most surprising of these arguably was the continued presence of recurrent 26-day variations in particle fluxes at both high and low energies. Recurrent MeV ion and 100 keV electron events (Sanderson et al., 1995; Simnett et al., 1995) were observed as well as recurrent depressions in the GeV cosmic ray flux (Simpson et al, 1995) at the highest latitudes reached by Ulysses, in a region where corresponding variation in the solar wind and magnetic field were no longer present.

The Ulysses observations, which imply an effective particle transport between low and high latitudes, prompted Fisk (1996) to re-investigate the structure of magnetic field lines in the large-scale heliospheric magnetic field (HMF). Fisk (1996) pointed out that the differential rotation in the photosphere and the non-radial expansion close to the Sun lead to an organized excursion of the footpoints of HMF lines which, in turn, results in an organized latitudinal motion of the field lines. This establishes an *organized* and *causal* magnetic connection between high and low latitudes. An alternative picture (Kóta and Jokipii, 1995, 1998) interprets the latitudinal transport as the result of perpendicular diffusion, primarily due to the random walk of field lines. The two mechanisms are not mutually exclusive, they may be at work at the same (Fisk and Jokipii, 1999).

Cosmic-ray transport in a Fisk type field is inherently 3-dimensional and poses serious challenges for both analytical and numerical models. Some aspects of modulation in a Fisk field have been discussed by Kóta and Jokipii (1995, 1997). The major problem for numerical simulations is that, speaking in technical terms, the presence of the very complex latitudinal field component introduces new mixed derivatives in the transport equation. Not only do these terms demand extra computing efforts but they also render the numerical schemes less stable. An additional technical difficulty is that field lines at the poles are in general not aligned to the radial direction thus the use of polar coordinates becomes problematic at best.

Studying the Fisk-field must call our attention to the potential role a regular B_ϑ component may play in general. For instance, almost any time variation in the large-scale field leads to a B_ϑ component. The inclusion of B_ϑ is inescapable when addressing time-dependent HMF. A global reorganization in the HMF generates, *inevitably*, a B_ϑ component. In a previous work (Kóta and Jokipii, 1999) we suggested a particular way to handle this problem by using *heliomagnetic coordinates*, which are attached to the field lines. This technique was applied successfully by Kóta and Jokipii (1983) and Hattingh and Burger (1995) to model cosmic-ray transport in a rigidly corotating Parker field with a tilted Heliospheric Current Sheet (HCS).

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We are developing a numerical code employing heliomagnetic coordinates. The use of heliomagnetic coordinates offers a promising avenue if diffusion is primarily field aligned. The subtleties of the field line geometry are probably less important if perpendicular diffusion due to the random mixing of field lines is effective. The code is custom designed to address cases when perpendicular diffusion is present but small.

In the present work we attempt to advance this concept. Kóta and Jokipii (1999) reported illustrative results with parallel diffusion only. In that approach, modulation is determined primarily by the length of the individual field lines between the observer and the outer boundary. Consequently the predicted variations were irreally large and are conceivably reduced when cross field transport due to perpendicular diffusion and drifts are also included. Numerical results are anticipated by the time of the Conference.

2 Equations in Heliomagnetic Coordinates:

The equation governing the variation of the omnidirectional cosmic-ray density, $f(x_i, p, t)$, in the position, x_i, momentum, p, and time, t, was written down by Parker (1965). In Cartesian coordinates:

$$\frac{\partial f}{\partial t} - \frac{\partial}{\partial x_i}\left(\kappa_{ij}\frac{\partial f}{\partial x_j}\right) + (V_j + V_{Dj})\frac{\partial f}{\partial x_j} = \frac{p}{3}\frac{\partial V_j}{\partial x_j}\frac{\partial f}{\partial p} + Q \quad (1)$$

where V_j and V_{Dj} are the convection and drift velocities, respectively. Q accounts for sources. The anisotropic diffusion tensor, κ_{ij}, can be written as

$$\kappa_{ij} = \kappa_\perp \delta_{ij} + (\kappa_\parallel - \kappa_\perp) b_i b_j \quad (2)$$

with $b_i = B_i/B$ denoting the unit vector pointing in the direction of the field.

What we call heliomagnetic coordinates is essentially using (beside the radial distance, r) the angular variables Θ and Φ, which identify the footpoints of the respective field line at a reference time, t_0. Then, Θ and Φ remain constant on a field line. This choice of curvilinear coordinates calls for the use of co-variant and contra-variant coordinates. The form of (2) for the diffusion tensor, expressed in covariant form, becomes

$$\kappa^{ij} = \kappa_\perp g^{ij} + (\kappa_\parallel - \kappa_\perp) b^i b^j \quad (3)$$

while Parker's equation (1) takes the form

$$\frac{\partial f}{\partial t} = \frac{1}{\sqrt{g}}\frac{\partial}{\partial x^i}\left(\sqrt{g}\kappa^{ij}\frac{\partial f}{\partial x^j}\right) + (V^j + V_D^j)\frac{\partial f}{\partial x^j} + p\frac{2V}{3r}\frac{\partial f}{\partial p} \quad (4)$$

where g is the determinant of the metric tensor, g_{ij}, and $g^{ij}g_{jk} = \delta^i_k$. The structure of the HMF and the geometry of the field lines appear in the metric tensor, g_{ij}, which will, in general, evolve in time according to the dynamics of the footpoints, and then propagate outward in radius at the solar wind speed, V. Since we consider galactic cosmic rays we disregarded the source term, Q. Furthermore we took $(\nabla \mathbf{V})$ assuming a uniform radial wind.

The virtue of magnetic coordinates is that the magnetic field has only one non-zero component, both b^Θ and b^Φ vanish. The components of the drift velocity, V_D^j, are easy to obtain, and the HCS can be defined as a $\Theta = const.$ surface. The random transverse field component suggested by Jokipii & Kóta (1989) to impede fast polar transport can be incorporated as well. At the same time, the method has its drawbacks and limitations. The metric tensor, g_{ij}, becomes ill-conditioned at large radii where the HMF is predominantly azimuthal. For similar reasons the solar wind speed should preferably be uniform, and the motion of footpoints needs to be regular and tractable.

3 Motion od Footpoints

In the simplest representation of the Fisk field (Fisk, 1996; Zurbuchen et al., 1997, Fisk and Jokipii, 1999) the motion of the footpoints is the combination of two rotations: a rigid corotation around the rotational axis of the Sun and an additional rotation around and offset axis. We shall first consider HMF models where the footpoint motion can be described as a rotation but the axis of rotation is allowed to vary in time.

In a more general model of a time-dependent HMF, the motion of footpoints on the Sun, $\mathbf{v}_{ft}$ determines the variation of the radial magnetic field, B_r, at the Sun

$$\frac{\partial B_r}{\partial t} + \nabla(\mathbf{v}_{ft} B_r) = 0 \quad (5)$$

We shall discuss various types of divergence-free motion of the footpoints. The geometry of the frozen-in field lines of the HMF carried by the solar wind is calculated assuming a uniform radial solar wind.

4 Summary

Numerical results, which are anticipated by the time of the Conference, will be presented.

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