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The Diffusion Tensor of Energetic Particles in Different Heliospheric Magnetic Field Configurations

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Abstract: The propagation of energetic particles in the heliosphere is described by the Parker transport equation. It includes the physical processes of diffusion, drift, convection and adiabatic energy changes. For the modulation of the particle's energy spectra the geometry of the heliospheric magnetic field is important, but it is still an unsolved problem. In this contribution we present model calculations of the particle mean-free-path in two different field configurations: the standard Parker geometry and a Fisk-Parker hybrid field. Results for both magnetic field models are shown comparatively and the implications for the particle transport are discussed.

Introduction

Energetic particle spectra are strongly modulated by the heliospheric magnetic field (HMF) and the solar wind (SW). The intensity of this influence varies periodically depending on the 22-year solar cyle, see e.g. Heber & Potgieter [4]. Especially the HMF changes its polarity and might undergo fundamental changes in its structure between solar maximum and minimum activity.

With the Ulysses spacecraft the possibility arose to study the propagation of energetic particles in all three dimensions of the heliosphere, [4] and references therein, and the question of the latitudinal transport gained more importance (Jokipii & Kóta [5], Ferreira [2]) but is still not fully answered.

Many models investigating particle modulation employ a Parker-type HMF configuration, see e.g. Ferreira [2] or Lange et al. [6]. But since the global structure of the HMF during solar minimum conditions is still an open question, its possible influence on the latitudinal particle diffusion has to be discussed also for Fisk-type fields, see e.g. Burger & Hitge [1].

Energetic Particles in the Heliosphere

The propagation of energetic particles in the heliosphere is described by the Parker transport equation [8]:

$$\frac{\partial f}{\partial t} = \underbrace{\vec{\nabla}\cdot\left(\hat{\kappa}'\left(\vec{\nabla}f\right)\right)}_{\text{diffusion \& drift}} - \underbrace{\vec{u}_{\rm SW}\cdot\left(\vec{\nabla}f\right)}_{\text{convection}} + \underbrace{\frac{1}{3}\left(\vec{\nabla}\cdot\vec{u}_{\rm SW}\right)\frac{\partial f}{\partial\left(\ln P\right)}}_{\text{adiabatic } \Delta\text{E}} + S \quad (1)$$

It includes the important physical processes influencing the particle's distribution function f. The diffusion and drift effects are described by a tensor $\hat{\kappa}'$ in the coordinate system of the heliospheric magnetic field

$$\hat{\kappa}' = \begin{pmatrix} \kappa_{\|} & 0 & 0 \\ 0 & \kappa_{\perp,\rm r} & \kappa_{\rm A} \\ 0 & -\kappa_{\rm A} & \kappa_{\perp,\vartheta} \end{pmatrix} \quad (2)$$

with $\kappa_{\|}$ for the diffusion parallel to the magnetic field lines, $\kappa_{\perp,\rm r}$ and $\kappa_{\perp,\vartheta}$ perpendicular to the field lines in radial (r) and latitudinal (ϑ) direction and

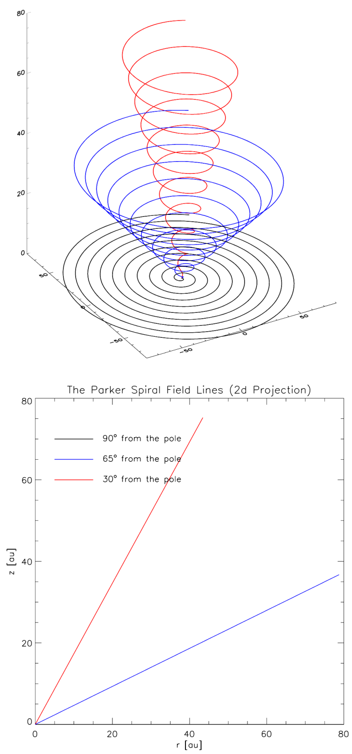

Figure 1: The Parker HMF configuration model in two different projections.

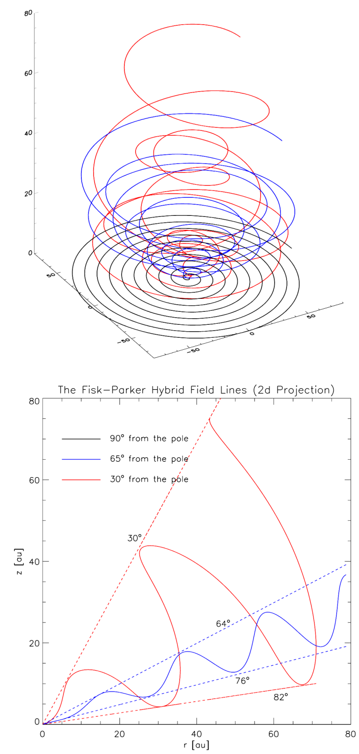

Figure 2: The Fisk-Parker hybrid HMF configuration model in two different projections.

κ_A for the drift effects. The solar wind is assumed to flow with a velocity $\vec{u}_{SW} = u_0\,(\mathrm{r},\vartheta)\,\vec{e}_\mathrm{r}$ radially away from the sun. The adiabatic energy changes are dependent on the particle rigidity P and S stands for the source term, e.g. galactic particles flowing into the heliosphere or jovian electrons.

In this contribution we study the influence of the global HMF configuration on the particle diffusion, so in the next section the two models used in this paper are presented.

The HMF configuration

After the magnetic field is frozen into the SW plasma, it is carried outwards with the SW flow to form the global HMF. Different approaches to explain its configuration were made in the past, e.g. by Parker [7] or Fisk [3]. Recently a hybrid model of the Fisk and Parker fields was suggested to describe the HMF at solar minimum by Burger & Hitge [1]. This is basically done by introducing a transition function to achieve a Parker-like field around the solar equator and at the poles and a Fisk-like field at mid- and higher latitudes (for details see [1]) with the restriction of an isotropic solar wind velocity, i.e. $\vec{u}_{SW}$ cannot be taken as a function of latitude like in the simple Parker field.

In our study we compare the influence of the simple Parker HMF and the Fisk-Parker hybrid field on the particle diffusion. Illustrations of both field models are presented in two different projections. Figures 1 and 2 display the field lines for the Parker (1) and the Fisk-Parker hybrid (2) models. In the upper panels the field is given in 3D, the lower panels show an unwinded 2D projection. For this presentation three field lines were constructed with three different starting positions of the footpoints to initiate the field line development.

As one can see, the Parker field is spiral-shaped and forms cones at higher latitudes since the magnetic field footpoints always stay at the same latitude. For a Fisk-type field like the Fisk-Parker hybrid the structure gets more complicated due to the latitudinal motion of the magnetic field footpoints on the source surface, see e.g. [3, 1]. The first implications for the particle propagation can be derived from the 2D projections of the field lines. Considering the latitudinal transport, in a Parker field the ϑ-diffusion has to be described as perpendicular to the field lines. In a Fisk-type field the latitudinal transport can actually be described as parallel to the field lines. Therefore the particle transport in polar direction will be influenced by the field geometry which will be discussed in the next section.

Energetic Particle Mean Free Path

For our calculations we employ the model for the diffusion tensor from Ferreira [2] for Jovian and galactic electrons, where the parallel diffusion is taken to be a function of the radial distance from the sun r and the particle rigidity P:

$$\kappa_\parallel = \kappa_0 \, \beta \, g\left(r, P\right) \qquad (3)$$

Here we assume $\kappa_0 = 4.5 \cdot 10^{22}$ cm^2/s and β is the ratio of the particle speed to the speed of light ($\beta = v/c$). The perpendicular diffusion coefficients are taken to be ratios to the parallel coefficient. In the Parker field we assume the same two different ratios that can be found in Ferreira [2]

$$\kappa_{\perp,\mathrm{r}} = 0.02 \, \kappa_\parallel \left(\frac{P}{P_0}\right)^{0.3} \qquad (4)$$

$$\kappa_{\perp,\vartheta} = 0.015 \, \kappa_\parallel \, F\left(\vartheta\right) \qquad (5)$$

where a function $F(\vartheta)$ is introduced into the latitudinal coefficient to enhance $\kappa_{\perp,\vartheta}$ at higher latitudes ($< 20^\mathrm{o}$) by a factor of six, while we use $\kappa_\perp = \kappa_{\perp,\mathrm{r}} = \kappa_{\perp,\vartheta}$ with the ratio given in eq. (4) in the Fisk-Parker hybrid model well knowing that this will have to be adjusted for modulation studies. But it will still lead to first qualitative results showing the principles of the HMF's influence on the perpendicular transport.

For further calculations the diffusion tensor, see eq. (2), is usually transformed from the magnetic field coordinate system to spherical polar coordinates. We present the mean free paths derived

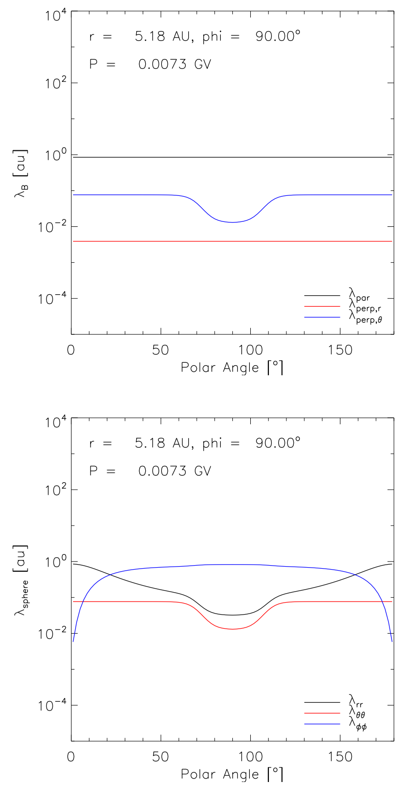

Figure 3: The particle mean free path depending on heliographic latitude in a Parker field model.

from the diffusion coefficients by the equation $\lambda_\mathrm{i} = 3\kappa_\mathrm{i}/v$ for both coordinate systems. The index i stands for the different directions of the diffusion, i.e. for ($\|$), ($\perp$,r) and ($\perp$,ϑ) in magnetic field coordinates and for the radial (rr), latitudinal ($\vartheta\vartheta$) and longitudinal ($\varphi\varphi$) directions in spherical polar coordinates.

Figure 3 shows the particle mean free path depending on the heliographic latitude with the solar north- and south pole at 0^o and 180^o at a distance of $r \approx 5$ AU from the sun (approx. Jupiter's orbit) and for a particle rigidity of $P \approx 7$ MV which is a typical value for Jovian electrons. The HMF configuration is a Parker field with a solar wind speed of 400 $\mathrm{km/s}$ in the equatorial region and 800 $\mathrm{km/s}$ at latitudes $> 20^\mathrm{o}$ north and south of the solar equator. The upper panel shows the mean free path in magnetic field coordinates. One can see that $\lambda_\parallel$ (black line) and $\lambda_{\perp,\mathrm{r}}$ (red line) do not depend on the latitude, while $\lambda_{\perp,\vartheta}$ (blue line) re-

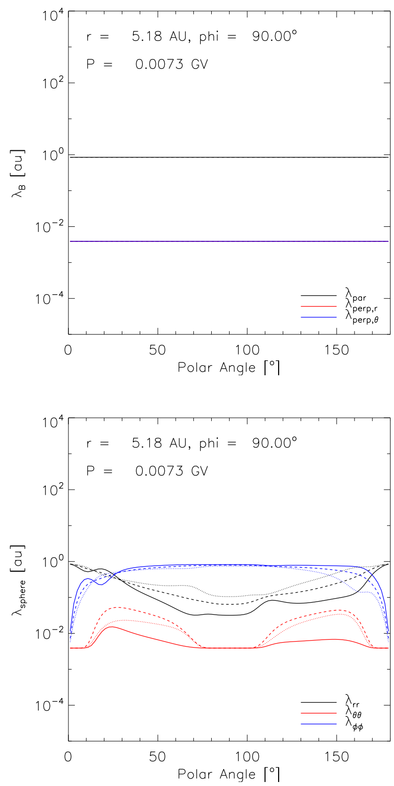

Figure 4: The same as Fig. 3 but for a Fisk-Parker hybrid field model.

flects the enhancement by the function $F(\vartheta)$. The lower panel displays the mean free path after the transformation to spherical polar coordinates. In the coefficients $\lambda_{\rm rr}$ (black line) and $\lambda_{\varphi\varphi}$ (blue line) the influence of the magnetic field structure can be seen, while there is no additional change in the latitudinal mean free path $\lambda_{\vartheta\vartheta}$ (red line) by the HMF configuration.

In Fig. 4 the particle mean free path is given for the Fisk-Parker hybrid field. The color coding and the parameters are the same as in Fig. 3. Since the Fisk-Parker hybrid field is calculated with an isotropic solar wind speed we present the mean free path for three different values of $u_{\rm SW}$: 400 km/s (solid lines), 600 km/s (dashed lines) and 800 km/s (dotted lines). One can see the mean free path in magnetic field coordinates in the upper panel. There is no latitudinal dependence in either of the coefficients. Because of $\lambda_{\perp,\rm r} = \lambda_{\perp,\vartheta}$ the corresponding lines lie on top of each other. Comparing the lower panel displaying the mean free path in spherical polar coordinates to the one in Fig. 3 one can see the influence of the more complex field structure even in the radial ($\lambda_{\rm rr}$) and longitudinal ($\lambda_{\varphi\varphi}$) transport. The clearest difference is the enhancement of $\lambda_{\vartheta\vartheta}$ just by the HMF configuration without assuming an additional ϑ-dependent function.

Conclusions

Comparing the results for the mean free path in the two different magnetic field models, one can say that a Fisk-type field like the Fisk-Parker hybrid (Burger & Hitge [1]) can at least partly explain the enhancement of the latitudinal transport. To what extent the global HMF structure or the magnetic field turbulence (Jokipii & Kóta [5]) are responsible for the high latitudinal diffusion is still an open question and part of ongoing discussions.

The strong effect we find close to Jupiter's orbit and for particle rigidities of Jovian electrons suggests that further investigation of the propagation of few-MeV electrons in a Fisk-type field and comparison to Ulysses measurements may contribute to the solution of the open question of the global HMF configuration by using particle propagation as a remote sensing method.

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