Time-dependent Propagation of 7 MeV Electrons in a Fisk-Parker Hybrid HMF

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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 inner heliosphere the Jovian magnetosphere is the dominant source of energetic electrons. Therefore the so-called Jovian electrons are nearly perfect test particles to study transport theories. In this contribution we present time-dependent model calculations of the electron flux in a Fisk-Parker hybrid heliospheric magnetic field configurations and compare our results to spacecraft data and a Parker-HMF-Model.**

***Keywords*: Particle Propagation, Heliospheric Magnetic Field, Jovian electrons**

I. 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 [2].

Many models investigating particle modulation employ a Parker-type HMF configuration, see e.g. Ferreira [3] 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].

II. Energetic Particles in the Heliosphere

The propagation of energetic particles in the heliosphere is described by Parker's transport equation

$$\frac{\partial f}{\partial t} = \vec{\nabla}\cdot\left(\hat{\kappa}\left(\vec{\nabla}f\right)\right) - \vec{u}_{\rm sw}\cdot\left(\vec{\nabla}f\right) + \frac{1}{3}\left(\vec{\nabla}\cdot\vec{u}_{\rm sw}\right)\frac{\partial f}{\partial\left(\ln P\right)} + S \qquad (1)$$

including all important physical processes influencing the particles' distribution function f. The diffusion is

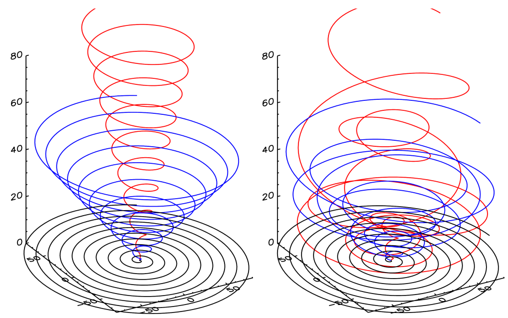

Fig. 1: The field line configuration in a Parker HMF (left panel) and a Fisk-Parker hybrid HMF (right panel).

described by a tensor $\hat{\kappa}$ in magnetic field aligned coordinates

$$\hat{\kappa} = \begin{pmatrix} \kappa_{\|} & 0 & 0 \\ 0 & \kappa_{\perp,\rm r} & 0 \\ 0 & 0 & \kappa_{\perp,\theta} \end{pmatrix} \qquad (2)$$

with $\kappa_{\|}$ for the diffusion along the field lines and $\kappa_{\perp,\rm r}$ and $\kappa_{\perp,\theta}$ perpendicular to the field lines in radial (r) and in latitudinal (θ) direction. Any drift effects can be neglected at these low energies discussed in this contribution.

III. The HMF Configuration

Different theories describing the HMF configuration were developed in the past. The most common model was published by Parker [7]. The field lines in this configuration are illustrated in the left panel of Fig. 1. Fisk [4] presented a different HMF model, which is valid inside persistent coronal holes, esp. the polar coronal holes during periods of solar minimum.

Burger & Hitge [1] suggest a Fisk-Parker hybrid HMF configuration during solar minimum (see right panel of Fig. 1). They introduce a transition function $F_{\rm s}$ depending on the heliographic latitude θ describing the crossover from a Parker field ($F_{\rm s} = 0$) to a Fisk field ($F_{\rm s} = 1$). Figure 2 shows $F_{\rm s}$ for the full latitudinal range from the solar north pole ($\theta = 0^{\circ}$) to the solar south pole ($\theta = 180^{\circ}$).

The plot illustrates the time development $F_{\rm s}$ as it is implemented in our modulation model for the transition

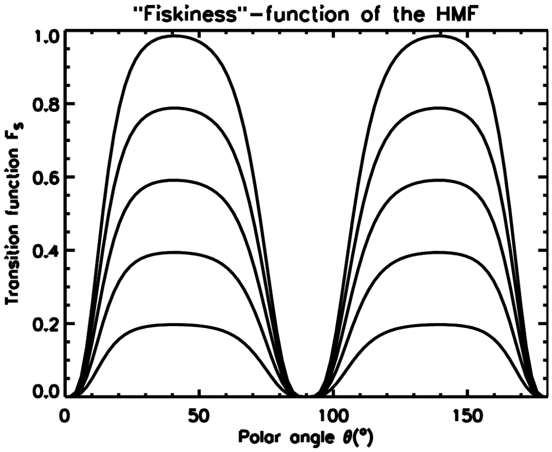

Fig. 2: The transition function F_s.

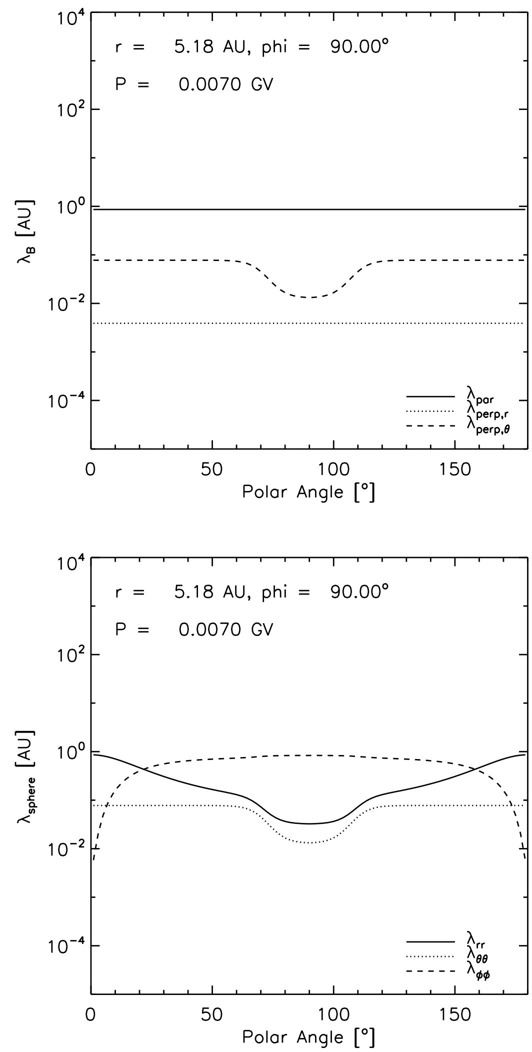

Fig. 3: The particle mean free path in a Parker HMF configuration depending on the heliographic latitude.

from solar maximum to solar minimum conditions. During solar maximum F_s becomes 0 for all latitudes. Towards solar minimum the fraction of the Fisk field rises at mid and high latitudes. The upper curve represents the configuration of the HMF during solar minimum conditions.

In this contribution we compare the influence on the propagation of 7 MeV electrons of the Fisk-type HMF described by Burger & Hitge [1], with a transition function as described above, to the pure Parker field. For this study we calculate the electron flux for the Ulysses trajectory and compare our results to Ulysses/KET measurements.

IV. THE 7 MEV ELECTRON FLUX IN A PARKER HMF

For our calculations with a Parker HMF we employ the diffusion tensor from Ferreira [3] who derived

$$\begin{aligned} \kappa_{\parallel} &= \kappa_0 \cdot f\,(r, P) \\ \kappa_{\perp,\mathrm{r}} &= \delta \cdot \kappa_{\parallel} \\ \kappa_{\perp,\theta} &= \varepsilon \cdot \kappa_{\parallel} \cdot F\,(\theta)\,, \end{aligned} \qquad (3)$$

where a function $F\,(\theta)$ is introduced to enhance $\kappa_{\perp,\theta}$ at higher latitudes ($< 20^\mathrm{o}$) during solar minimum motivated by high turbulence in the fast solar wind (Jokipii et al. [5]). During solar maximum $F\,(\theta)$ becomes unity.

The particle mean free path $\lambda = 3\kappa/v$, with the particle speed v, during solar minimum conditions is displayed in Fig. 3 depending on the heliographic latitude at a distance of $r \approx 5$ AU to the sun and for a particle rigidity of $P = 7$ MV which is a typical value for Jovian electrons. The solar north- and south pole are placed at 0^o and 180^o, respectively. The HMF configuration is a Parker field with a solar wind speed of $u_\mathrm{sw} \approx 400$ km/s in the equatorial region and $u_\mathrm{sw} \approx 800$ km/s at latitudes $< 20^\mathrm{o}$. The upper panel displays the particle mean free path in a coordinate system aligned to the magnetic field structure. The plot shows that $\lambda_{\parallel}$ (solid line) and $\lambda_{\perp,\mathrm{r}}$ (dotted line) do not depend on the latitude θ, while $\lambda_{\perp,\theta}$ (dashed line) shows the enhancement by the function $F\,(\theta)$. The lower panel shows the mean free path after the transformation to a spherical polar coordinate system with the Sun in the center. The influence of the magnetic field structure becomes evident in the coefficients λ_rr (solid line) and $\lambda_{\phi\phi}$ (dashed line), while $\lambda_{\theta\theta}$ (dotted line) shows no additional change due to the magnetic field.

The 7 MeV electron flux for the Ulysses trajectory resulting from this model configuration is displayed in Fig. 5. The upper panel illustrates the trajectories of both Ulysses (red lines) and Jupiter (black lines). The solid lines stand for the latitudinal coordinate, the dashed lines stand for the radial distance to the Sun. The lower panel shows Ulysses/KET measurements of electrons in the energy range of 2.5 MeV up to 7 MeV (gray line). Our model results are given by the three black lines (total electron flux, Jovian electrons and galactic electrons). The two Jupiter encounters lead to two high enhancements in 1992 and 2004. The other three ecliptic crossings lead to smaller increases in 1995, 2001 and 2008. The high flux level between 1997 and 2001 even

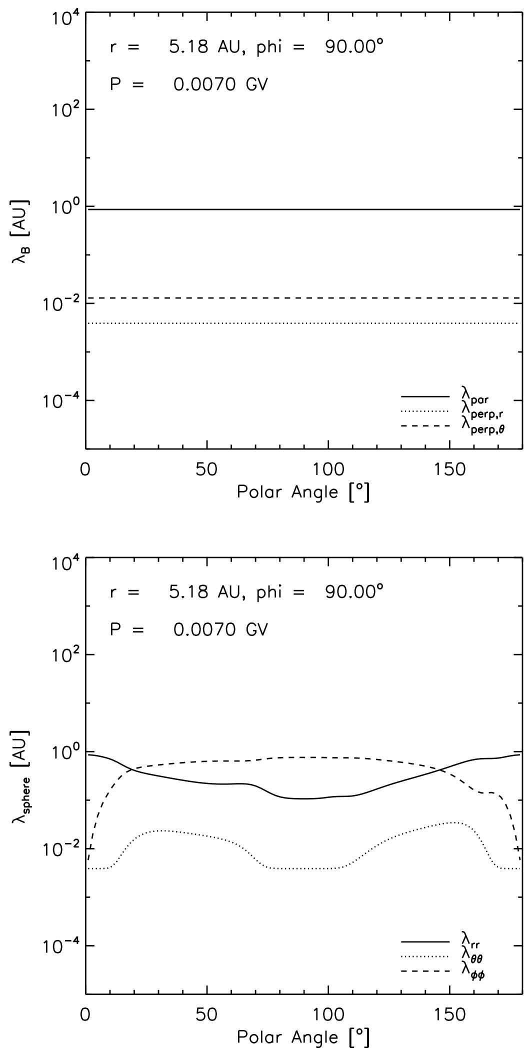

Fig. 4: The particle mean free path in a Fisk-Parker hybrid HMF configuration depending on the heliographic latitude.

at high latitudes can be explained by the enhancement of the latitudinal diffusion, as was suggested by Jokipii et al. [5] and implemented into modulation studies, e.g. by Ferreira [3] and Lange et al. [6].

V. The 7 MeV Electron Flux in a Fisk-Parker Hybrid HMF

A different approach explaining the increased latitudinal diffusion during solar minimum was suggested by Fisk [4]. A complex HMF structure with a latitudinal component leads to magnetic field lines connecting the equatorial region to high latitudes. Therefore, charged particles can propagate along the field lines in latitudinal direction more easily, which leads to an enhanced transport in the polar direction.

Describing the diffusion in the hybrid field, we use the diffusion tensor mentioned above, but with $F(\theta)$ set to unity, see Fig. 4. The upper panel shows the mean free path in magnetic field coordinates. All three components are independent of the latitude. The lower panel displays the mean free path in spherical polar coordinates. After the transformation to this coordinate system, the increase in the latitudinal transport ($\lambda_{\theta\theta}$) due to the structure of the HMF field lines becomes visible.

The resulting 7 MeV electron flux for the Ulysses trajectory in the case of a Fisk-Parker hybrid field is part of ongoing work and will be presented at the conference.

VI. Conclusions

The model results for the 7 MeV electron flux show that the Parker HMF with the assumption of an enhanced latitudinal transport during solar minimum (see also Ferreira [3]) can reproduce the Ulysses measurements. A comparison of these data to the forthcoming calculations for the Fisk-Parker hybrid field and further investigation of particle propagation using different HMF models will contribute to the open question of the global HMF configuration.

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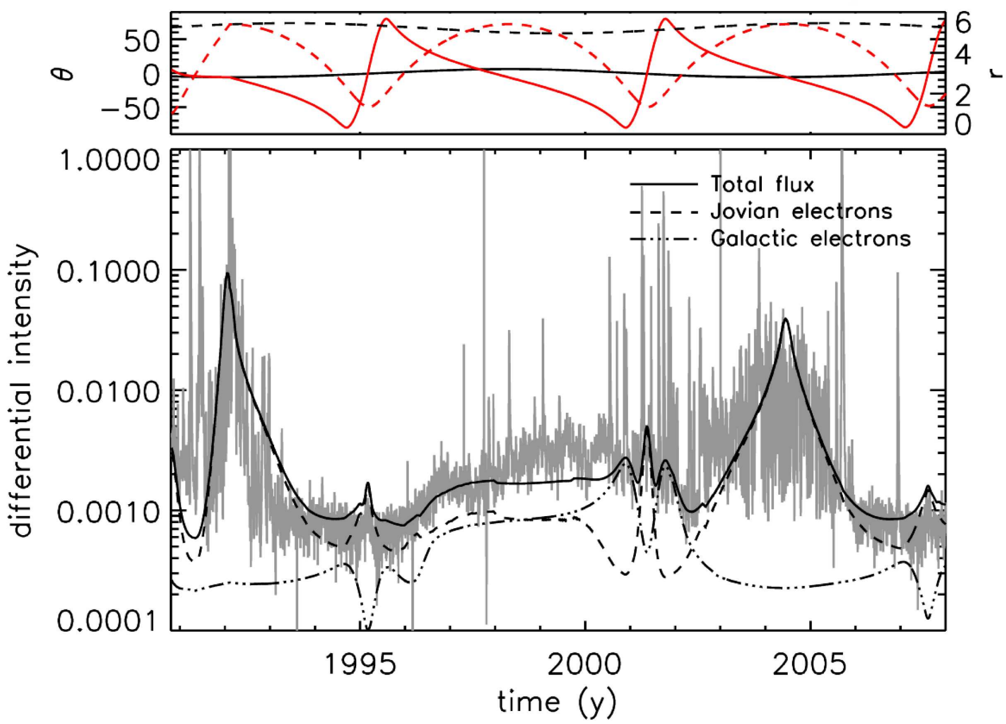

Fig. 5: A comparison of the $2.5 - 7$ MeV electrons measured by Ulysses to our model data in a Parker HMF.