Parallel and Perpendicular Transport of Charged Particles in the Solar System

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1 Introduction

Transport of charged cosmic rays in the interplanetary space was discussed by many authors (e.g. Jokipii 1966, Bieber et al. 1994) and remains an interesting and important field of astrophysical research. One theoretical challenge is the understanding of observed mean free paths of the cosmic particles which experience scattering parallel and perpendicular to the magnetic field of the sun $\vec{B}_0$.

Here we compare different theoretical results for parallel diffusion with the Palmer consensus (Palmer 1982) and pickup ion observations (Gloeckler et al. 1995, Möbius et al. 1998). Theoretical results for perpendicular diffusion are compared with the Palmer consensus (Palmer 1982), Jovian electrons (Chenette et al. 1977), and Ulysses measurements of Galactic protons (Burger et al. 2000).

If a diffusion coefficient is calculated theoretically, the turbulence properties have to be specified by specifying the correlation tensor: $P_{lm}(\vec{k},t) = \left\langle \delta B_l(\vec{k},t) \delta B_m^*(\vec{k},0) \right\rangle$ which is determined by the wave spectrum (wavenumber dependence of $P_{lm}(\vec{k},t)$), the turbulence geometry (orientation of $\vec{k}$ relative to $\vec{B}_0$), and the time-dependence of $P_{lm}(\vec{k},t)$. To specify the wavespectrum for instance, we can use observations (e.g. Denskat & Neubauer 1982). Such a measured spectrum can be divided into three intervals which can easily be distinguished: for small wavenumber we find a flat spectrum which can be approximated by a constant (energy-range), for intermediate wavenumbers we find a kolmogorov-like behaviour ($\sim k^{-5/3}$, inertial-range), and for large wavenumbers a steep behaviour can be seen ($\sim k^{-3}$, dissipation-range). Also the turbulence geometry can be obtained from measurements. According to Bieber et al. (1994), a composite model which consists of a superposition of a slab model ($\vec{k} \parallel \vec{B}_0$) and a 2D model ($\vec{k} \perp \vec{B}_0$) should be appropriate. More difficult to specify is the time-dependence. By introducing the dynamical correlation function $\Gamma(\vec{k},t)$, the correlation tensor can be written as $P_{lm}(\vec{k},t) = P_{lm}(\vec{k})\Gamma(\vec{k},t)$. In the following section we discuss several models for the wave spectrum, the turbulence geometry, and the function $\Gamma(\vec{k},t)$.

2 The standard quasilinear approach

An early treatment of particle transport employed the standard quasilinear theory (SQLT, Jokipii 1966) where a magnetostatic slab model ($\Gamma(\vec{k},t) = 1$) and a wave spectrum without dissipation-range were combined with the quasilinear approach. Palmer (1982) compared the predictions of SQLT for the parallel mean free path with heliospheric observations and noted two major problems:

1) the observed parallel mean free paths are typically much larger than the predicted SQLT results (magnitude problem);

2) the observed parallel mean free paths are generally constant with a rigidity independent mean free path for 0.5 to 5000 MV, but SQLT predicts that the mean free path should increase with increasing rigidity (flatness problem).

3 The model of Bieber et al. 94

Because of the disagreement between SQLT and the observed parallel mean free paths, Bieber et al. (1994) proposed an improved turbulence model:

1) They replaced the static model by two different dynamical turbulence models. In the damping model of dynamical turbulence the dynamical correlation function is $\Gamma(\vec{k},t) = \exp(-\alpha v_A \mid k \mid t)$ and in the random sweeping model $\Gamma(\vec{k},t) = \exp(-(\alpha v_A k t)^2)$. In both models a parameter α was introduced to adjust the strength of dynamical effects.

2) In agreement with observations, they replaced the slab model by a 20% slab / 80% 2D composite model.

3) They assumed that the 2D contribution to parallel scattering can be neglected.

4) They used a realistic wave spectrum with energy-, inertial- and dissipation-range.

As demonstrated in several articles (e. g. Bieber et al. 1994, Dröge 2000), a combination of QLT with the damping model of dynamical turbulence is able to reproduce the observed parallel mean free path. However, there are several problems assoziated with the Bieber et al. (1994) approach. First, the form $\Gamma(\vec{k},t) = \exp(-\alpha v_A \mid k \mid t)$ and the parameter α cannot be derived theoretically. Furthermore, plasma wave effects are neglected in the damping and random sweeping model. The most serious problem is that the observed perpendicular mean free paths cannot be reproduced by combining QLT with such dynamical turbulence models (Shalchi & Schlickeiser, 2004).

4 The NADT-model

To solve these problems we recently proposed a new turbulence model, which we call the "Nonlinear Anisotropic Dynamical Turbulence model" (NADT-model, Shalchi et al. 2006). In this model we still assume composite geometry and the wavespectrum used in Bieber et al. (1994), but we assumed different forms of the slab and the 2D dynamical correlation functions: $P_{lm}(\vec{k},t) = P_{lm}^{slab}(\vec{k})\Gamma^{slab}(k_\parallel,t) + P_{lm}^{2D}(\vec{k})\Gamma^{2D}(k_\perp,t)$.

In earlier treatments of dynamical turbulence, the decorrelation factors $\Gamma^i(\vec{k},t)$ were established using simple approximations to the interactions responsible for temporal decorrelation of excitations near wave vector $\vec{k}$. In random sweeping and damping models, for example, a single parameter is introduced to estimate the rate of decorrelation at scale $1/k$ and this is assumed to be related to the Alfvén speed v_A. To improve these models, we note that in recent years there has been a more complete understanding of the time scales of MHD turbulence (e.g. Zhou et al. 2004), and the relation these may have to interactions between excitations that may be associated with either low frequency or wavelike components of the turbulence spectrum (Matthaeus et al. 1990, Tu & Marsch, 1993, Oughton et al. 2006). These ideas may be used to determine reasonable approximations to the functions $\Gamma^{slab}(\vec{k},t)$ and $\Gamma^{2D}(\vec{k},t)$ (for details see Shalchi et al. 2006):

$$\Gamma^{slab}(k_\parallel,t) = e^{-t/\tau_{slab}} \cdot e^{i\omega t}, \quad \Gamma^{2D}(k_\perp,t) = e^{-t/\tau_{2D}} \tag{1}$$

with the dispersion relation of shear Alfvén waves $\omega = v_A k_\parallel$, the slab correlation time-scale

$$\tau_{slab}^{-1} = \sqrt{2}\frac{v_A}{l_{2D}}\frac{\delta B_{2D}}{B_0} \tag{2}$$

and the 2D correlation time-scale

$$\tau_{2D}^{-1} = \sqrt{2}\frac{v_A}{l_{2D}}\frac{\delta B_{2D}}{B_0}\begin{cases} 1 & \text{for } k_\perp l_{2D} \leq 1 \\ (k_\perp l_{2D})^{2/3} & \text{for } k_\perp l_{2D} \geq 1 \end{cases} \tag{3}$$

Another problem is the invalidity of QLT for perpendicular transport. By using test-particle simulations, it can be demonstrated that QLT is not correct for describing perpendicular scattering. Thus a nonlinear tranport theory has to be applied for computing the perpendicular mean free paths. Here we apply the so-called nonlinear guiding center theory (NLGC-theory) of Matthaeus et al. (2003). For our calculations we used the following parameters:

Parameter	Symbol/Value
Inertial range spectral index	$2\nu = 5/3$
Dissipation range spectral index	$p = 3$
Alfvén speed	$v_A = 33.5\ km/s$
Mean field	$B_0 = 4.12\ nT$
Turbulence strength	$\delta B/B_0 = 1$
Slab fraction	$\delta B_{slab}^2 = 0.2 \cdot \delta B^2$
2D fraction	$\delta B_{2D}^2 = 0.8 \cdot \delta B^2$
Slab bendover scale	$l_{slab} = 0.030\ AU$
Slab dissipation wavenumber	$k_{slab} = 3 \cdot 10^6\ (AU)^{-1}$
2D bendover scale	$l_{2D} = 0.1 \cdot l_{slab}$
2D dissipation wavenumber	$k_{2D} = 3 \cdot 10^6\ (AU)^{-1}$

According to Figs. 1 and 2, a combination of the NADT-model, QLT and NLGC-theory can explain the observed parallel and perpendicular mean free paths in the heliosphere.

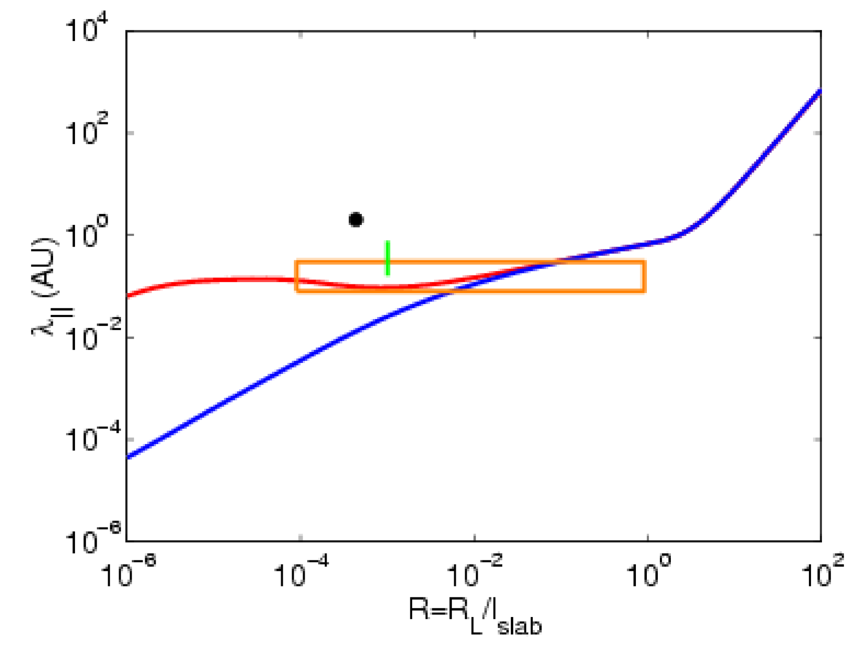

Fig. 1: The parallel mean free path $\lambda_\parallel$ versus $R = R_L/l_{slab}$ (R_L =Larmor-radius, l_{slab} =slab bendover scale) obtained within the NADT-model. Shown are QLT results for electrons (red) and protons (blue) in comparison with the Palmer consensus (Palmer 1982, orange), Ulysses observations (Gloeckler et al. 1995, black) and AMPTE spacecraft observations (Möbius et al. 1998, green). The discrepancy between the different observations can easily be understood: the Gloeckler et al. (1995) result for instance, was at a heliocentric distance of 2.34 AU, whereas the other observations were at 1 AU.

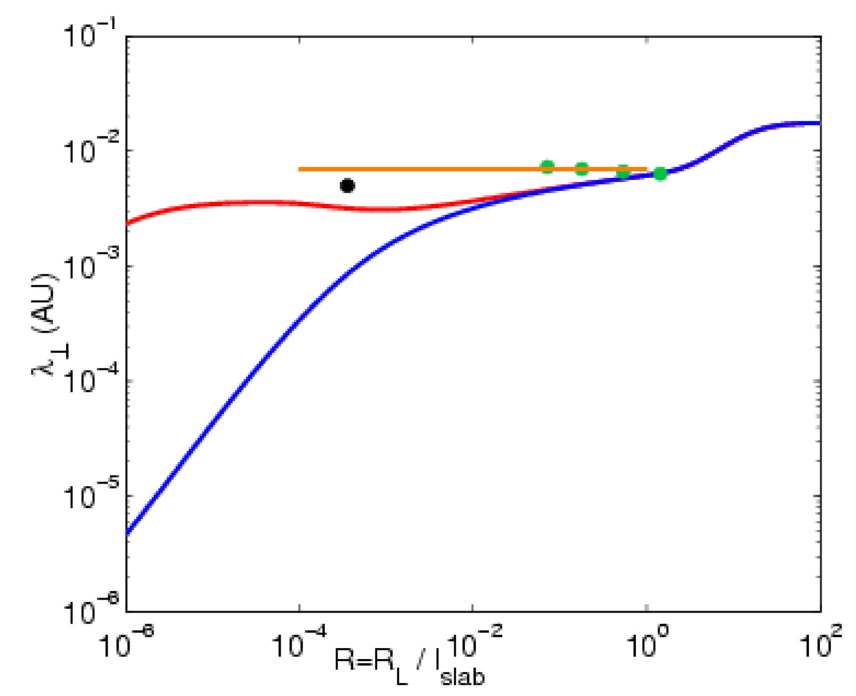

Fig. 2: The perpendicular mean free path $\lambda_\perp$ versus $R = R_L/l_{slab}$ obtained within the NADT-model. Shown are the NLGC-results for electrons (red) and protons (blue) in comparison with the Palmer consensus (1982, orange), Jovian electrons (Chenette et al. 1977, black) and Ulysses measurements of Galactic protons (Burger et al. 2000, green).

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