Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008
Vol. 1 (SH), pages 409–412

30TH INTERNATIONAL COSMIC RAY CONFERENCE

Parallel and Perpendicular Transport of Charged Particles in the Solar System

A. SHALCHI[1], J. W. BIEBER[2], W. H. MATTHAEUS[2], AND R. SCHLICKEISER[1]
[1]*Institut für Theoretische Physik, Lehrstuhl IV: Weltraum- und Astrophysik, Ruhr-Universität Bochum, D-44780 Bochum, Germany*
[2] *Bartol Research Institute and Department of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA*
andreasm4@yahoo.com

Abstract: A key problem of cosmic ray astrophysics is the explanation of measured parallel and perpendicular mean free paths in the heliosphere. Previous approaches used quasilinear theory in combination with simple turbulence models to reproduce heliospheric observations. Because of recent progress in transport and turbulence theory we present linear and nonlinear diffusion coefficients within an improved dynamical turbulence model to demonstrate that the observed mean free paths can indeed be reproduced theoretically.

Introduction

Transport of charged cosmic rays in the interplanetary space was discussed by many authors [1, 2] 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 $\vec{B}_0$.

In this article we compare different theoretical results for parallel diffusion with the Palmer consensus [3] and pickup ion observations [4, 5]. Theoretical results for perpendicular diffusion are compared with the Palmer consensus, Jovian electrons [6], and Ulysses measurements of Galactic protons [7].

If a diffusion coefficient is calculated theoretically, the turbulence properties have to be specified by specifying the correlation tensor: $P_{lm}(\vec{k},t) =< \delta B_l(\vec{k},t)\delta B^*_m(\vec{k},0) >$ which is determined by the wave spectrum (wavenumber dependence of P_{lm}), the turbulence geometry (orientation of $\vec{k}$ relative to the background field $\vec{B}_0$), and the time-dependence of $P_{lm}(\vec{k},t)$. To specify the wavespectrum, we can use observations [8]. 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. [2], 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. Bieber et al. [2] suggested that 20% slab and 80% 2D should be realistic. 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 $P_{lm}(\vec{k},t) = P_{lm}(\vec{k})\Gamma(\vec{k},t)$. Prominent models for $\Gamma(\vec{k},t)$ are the magnetostatic model ($\Gamma(\vec{k},t) = 1$), the plasma wave model ($\Gamma(\vec{k},t) = e^{i\omega t}, \omega =$plasma wave dispersion relation), and dynamical turbulence models (e.g. $\Gamma(\vec{k},t) = e^{-t/\tau}, \tau =$correlation timescale). Furthermore, the turbulence parameters have to be specified. As shown in Table 1, the most parameters can be obtained from observations. In the following we discuss different previous approaches which were proposed to reproduce heliospheric observations of the mean free paths.

Parameter	Symbol/Value
IR spectral index	$2\nu = 5/3$
DR 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	$\delta B^2_{slab} = 0.2 \cdot \delta B^2$
2D fraction	$\delta B^2_{2D} = 0.8 \cdot \delta B^2$
Slab bendover scale	$l_{slab} = 0.030\ AU$
Slab DR wavenumber	$k_{slab} = 3 \cdot 10^6\ (AU)^{-1}$
2D bendover scale	$l_{2D} = 0.1 \cdot l_{slab}$
2D DR wavenumber	$k_{2D} = 3 \cdot 10^6\ (AU)^{-1}$

Table 1: The turbulence parameters used for our calculations. These values should be appropriate for 1 AU heliocentric distance. IR stands for inertial-range and DR for dissipation-range.

The standard quasilinear approach

An early treatment of particle transport employed the standard quasilinear theory (SQLT, [1]) where a simplified turbulence model was combined with the quasilinear approach. This turbulence model assumes magnetostatic slab turbulence and a wave spectrum without dissipation-range. To examine their validity, the SQLT-results can be compared with test particle simulations [9]. Whereas the results for parallel diffusion can be confirmed by these simulations, the results for perpendicular diffusion cannot be confirmed. Thus, QLT is not appropriate for perpendicular transport. Palmer [3] 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).

The turbulence model of Bieber et al. 94

Because of the disagreement between SQLT and the observed parallel mean free paths, Bieber et al. [2] proposed an improved turbulence model:
1) They replaced the magnetostatic 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. A justification for this assumption was given some years later by Shalchi & Schlickeiser [10].
4) They used a realistic wave spectrum with energy-, inertial- and dissipation-range in agreement with observations.

As demonstrated in several previous articles [2, 10, 11], a combination of QLT and the damping model of dynamical turbulence is able to reproduce the observed parallel mean free paths. However, there are several problems assoziated with the Bieber et al. [2] 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 [12].

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, [13]). In this model we still assume composite geometry and the wavespectrum used in Bieber et al. [2], but we assumed different forms of the slab and the 2D dynamical correlation functions: $P_{lm}(\vec{k},t) = P^{slab}_{lm}(\vec{k})\Gamma^{slab}(k_\parallel,t) + P^{2D}_{lm}(\vec{k})\Gamma^{2D}(k_\perp,t)$. For the functions $\Gamma^{slab}(\vec{k},t)$ and $\Gamma^{2D}(\vec{k},t)$ we use

$$\begin{aligned} \Gamma^{slab}(k_\parallel,t) &= e^{-t/\tau_{slab}} \cdot e^{i\omega t}, \\ \Gamma^{2D}(k_\perp,t) &= e^{-t/\tau_{2D}} \end{aligned} \qquad (1)$$

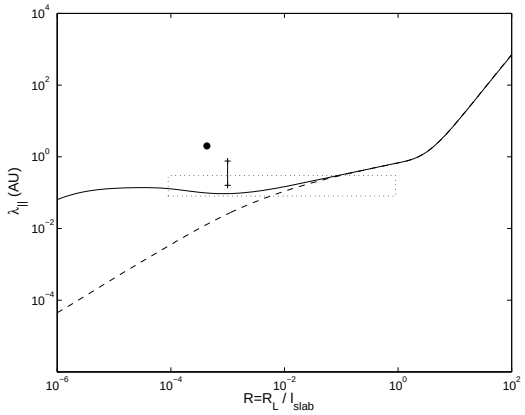

Figure 1: The parallel mean free path $\lambda_\parallel$ versus $R = R_L/l_{slab}$ (R_L =Larmor-radius, l_{slab} =slab bendover scale) obtained within the NADT-model. Shown are QLT results for electrons (solid line) and protons (dashed line) in comparison with the Palmer consensus ([3], box), Ulysses observations ([4], dot) and AMPTE spacecraft observations ([5], vertical line).

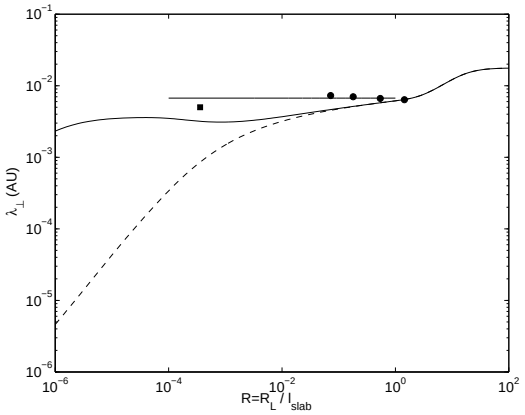

Figure 2: The perpendicular mean free path $\lambda_\perp$ versus $R = R_L/l_{slab}$ obtained within the NADT-model. Shown are the NLGC-results for electrons (solid line) and protons (dashed line) in comparison with the Palmer consensus ([3], horizontal line), Jovian electrons ([6], square) and Ulysses measurements of Galactic protons ([7], dots).

(for details see section 2.2 of [13]) 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

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

The NADT-model is defined through Eqs. (1) - (3). Another problem is the invalidity of QLT for perpendicular transport. By using test-particle simulations, it can be demonstrated that perpendicular scattering behaves diffusively for the slab/2D composite model [9]. Within QLT, however, we find superdiffusive transport [12]. So far only two theories are able to achieve agreement with the simulations: the NLGC-theory of Matthaeus et al. [14] and the weakly nonlinear theory (WNLT) of Shalchi et al. [15]. Although the WNLT has some advantages (e.g. one theory for parallel and perpendicular diffusion) we employ the NLGC-approach because this theory is more tractable. For our calculations we used the parameters illustrated in Table 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 (for a detailed discussion see [13]). Fig. 3 shows the ratio of perpendicular and parallel mean free paths as a function of the magnetic rigidity.

Conclusion and future work

As demonstrated, the NADT-model in combination with QLT for parallel diffusion and NLGC-theory for perpendicular diffusion can reproduce the heliospheric observations (see Figs. 1 and 2). In recent articles (e.g. [15]), however, it was demonstrated that nonlinear effects are in general also important if the parallel mean free path is calculated. Although the nonlinear effects are strong for the turbulence parameters considered in the simulations, QLT could be recovered for parallel diffusion for other parameter regimes and for dynamical turbulence.

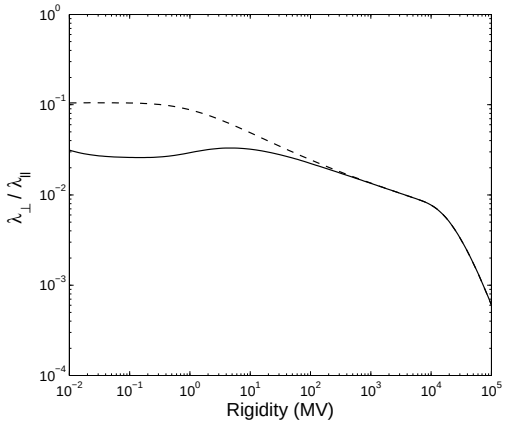

Figure 3: The ratio $\lambda_\perp/\lambda_\parallel$ versus the magnetic rigidity in Megavolt units obtained within the NADT-model.

References

[1] J. R. Jokipii. Cosmic-Ray Propagation. I. Charged Particles in a Random Magnetic Field. *Astrophys. J.*, 146:480-487, 1966.

[2] J. W. Bieber, W. H. Matthaeus, C. W. Smith, W. Wanner, M.-B. Kallenrode, and G. Wibberenz. Proton and electron mean free paths: The Palmer consensus revisited. *Astrophys. J.*, 420:294-306, 1994.

[3] I. D. Palmer. Transport coefficients of low-energy cosmic rays in interplanetary space. *Reviews of Geophysics and Space Physics*, 20:335-351, 1982.

[4] G. Gloeckler, N. A. Schwadron, L. A. Fisk, and J. Geiss. Weak pitch angle scattering of few MV rigidity ions from measurments of anisotropies in the distribution function of interstellar pickup H+. *Geophys. Res. Lett.*, 22:2665-2668, 1995.

[5] E. Möbius, D. Rucinski, M. A. Lee, and P. A. Isenberg. Decreases in the antisunward flux of interstellar pickup He+ associated with radial interplanetary magnetic field. *J. Geophys. Res.*, 10:257, 1998.

[6] D. L. Chenette, T. F. Conlon, K. R. Pyle, and J. A. Simpson. Observations of Jovian electrons at 1 AU throughout the 13 month Jovian synodic year. *Astrophys. J.*, 215:L95-L99, 1977.

[7] R. A. Burger, M. S. Potgieter, and B. Heber. Rigidity dependence of cosmic ray proton latitudinal gradients measured by the Ulysses spacecraft: Implications for the diffusion tensor. *J. Geophys. Res.*, 105:27447-27456, 2000.

[8] K. U. Denskat and F. M. Neubauer. Observations of hydrodynamik turbulence in the solar wind. In *Solar Wind Five, (Ed.) Neugebauer, M., Proceedings of a conference held in Woodstock, Vermont, November 1-5, 1982, vol. 2280 of NASA Conference Publication, pp. 81-91, NASA, Washington*. *J. Geophys. Res.*, 87:2215-2223, 1982.

[9] G. Qin, W. H. Matthaeus, and J. W Bieber. Perpendicular Transport of Charged Particles in Composite Model Turbulence: Recovery of Diffusion. *Astrophys. J.*, 578:L117-L120, 2002.

[10] A. Shalchi and R. Schlickeiser. The Parallel Mean Free Path of Heliospheric Cosmic Rays in Composite Slab/Two-dimensional Geometry. I. The Damping Model of Dynamical Turbulence. *Astrophys. J.*, 604:861-873, 2004.

[11] W. Dröge. Particle Scattering by Magnetic Fields. *Space Science Reviews*, 93:121-151, 2000.

[12] A. Shalchi and R. Schlickeiser. Quasilinear perpendicular diffusion of cosmic rays in weak dynamical turbulence. *Astrophys. J.*, 420:821-832, 2004.

[13] A. Shalchi, J. W. Bieber, W. H. Matthaeus, and R. Schlickeiser. Parallel and Perpendicular Transport of Heliospheric Cosmic Rays in an Improved Dynamical Turbulence Model. *Astrophys. J.*, 642:230-243, 2006.

[14] W. H. Matthaeus, G. Qin, J. W Bieber, and G. P. Zank. Nonlinear Collisionless Perpendicular Diffusion of Charged Particles. *Astrophys. J.*, 590:L53-L56, 2003.

[15] A. Shalchi, J. W. Bieber, W. H. Matthaeus, and G. Qin. Nonlinear Parallel and Perpendicular Diffusion of Charged Cosmic Rays in Weak Turbulence. *Astrophys. J.*, 616:617-629, 2004.