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ORIGINAL ARTICLE

The different transport regimes of pitch-angle scattering of energetic particles

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Abstract Recently an advanced nonlinear diffusion theory for particle transport across the mean magnetic field has been developed. The method used in the derivation of the latter theory is based on the cosmic ray Fokker-Planck equation. In the present article we use the same approach to describe pitch-angle scattering and parallel spatial diffusion nonlinearly. Furthermore, we derive the quasilinear transport theory, the weakly nonlinear theory as well as the Bohm limit as special cases from our more general approach.

Keywords Diffusion · Magnetic fields · Turbulence

1 Introduction

The interaction between energetic particles and a turbulent plasma is a fundamental problem of theoretical astrophysics. Charged particles such as cosmic rays interact with large scale magnetic fields such as the solar magnetic field or the Galactic magnetic field. These fields force the particles to follow helical orbits which can easily be computed by solving the Newton-Lorentz equation if this magnetic field is constant. Apart from the problem that real magnetic fields are not constant, one also has to take into account that there are the turbulent fields of the solar wind plasma or the interstellar plasma. These turbulent fields scatter particles so that they move diffusively.

In particle diffusion theory one has to distinguish between transport along and across the large scale magnetic field. Parallel and perpendicular diffusion are very different because different physical effects lead to these two scattering effects. Parallel diffusion, for instance, is caused by pitch-angle scattering preventing the particles from moving with constant velocity along the mean field. Perpendicular diffusion is mainly caused by the wandering of magnetic fields lines.

In the quantitative description of magnetic fields and charged particles we usually assume that the total magnetic field can be written as

$$\vec{B}(\vec{x}, t) = B_0 \vec{e}_z + \delta \vec{B}(\vec{x}, t) \tag{1}$$

where B_0 is the large scale/mean magnetic field and $\delta \vec{B}$ is the turbulent component. Here and in the following we choose a Cartesian system of coordinates so that the z-axis points in the direction of the mean field.

One can consider a weak turbulence environment where we have by definition $\delta B \ll B_0$. In this case one could assume that the true particle orbit is almost equal to the unperturbed orbit[1] and one could make the attempt to use a perturbation theory approach. The latter approach is usually called quasilinear theory (QLT) and was originally developed by Jokipii (1966). Perturbation theory or quasilinear theory, however, leads to some problems if the parallel diffusion coefficient is considered. The first problem is the 90° scattering problem and the second one is the so-called geometry problem (see Shalchi 2009a for a review). Furthermore, perpendicular diffusion cannot be described by perturbation theory because pitch-angle scattering usually disturbs the unperturbed orbits before the particles reach the diffusive regime (see again Shalchi 2009a for details).

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[1] If the turbulent magnetic fields would be zero, the particle orbit would be a perfect helical motion. This trajectory is usually called the unperturbed orbit.

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