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On the mean free path of solar cosmic rays

G. Michałek[1] **& M. Ostrowski**
Obserwatorium Astronomiczne, Uniwersytet Jagielloński, Kraków, Poland ([1]e-mail: michalek@oa.uj.edu.pl)

Abstract

The spatial transport of charged particles in a mixture of a finite amplitude magnetosonic and Alfvénic turbulence is considered using the Monte Carlo particle simulations. We show that dependence of the mean free path on particles rigidity is not modified significantly from the pure Alfvénic turbulence case. We note substantial mean free path differences for the considered magnetic field models, depending on the form of the considered turbulence spectrum.

1 Introduction:

Observations of solar energetic particle events confirm that energetic particle transport in the heliosphere must be considered as a diffusive process. Understanding the mechanism by which particles are scattered in cosmic plasma continues to be one of the most important problems of modern cosmic-ray physics. The main physical process underlying diffusive propagation is assumed to be pitch-angle scattering by magnetic fluctuations imposed on the large-scale magnetic field. This interaction is usually described by the quasi-linear theory (QLT)(e.g. Jokipii 1966, Schlickeiser 1989). Fitting cosmic-ray observations to diffusion models, especially determination of representative values of the scattering mean free path in solar energetic particle events, is one of the most severe tests a of that theory. In 1982 Palmer compared the predictions of QLT with observations and noted two major discrepancies. First, the observed mean free paths are typically an order of magnitude larger than the theoretical mean free paths. Secondly, the observations in the energy range from 0.5 to 5000 MeV are broadly consistent with a weak dependence of the mean free path on rigidity, while the theory predicts the strong decrease of the mean free path with decreasing particle rigidity. To resolve both these discrepancies Schlickeiser and Miller (1998), have calculated the quasilinear transport for cosmic rays resonantly interacting with a mixture of isotropic magnetosonic and slab Alfvén waves. They found that the particles are essentially accelerated by transit time damping due to interactions with magnetosonic waves (see also Michałek et al. 1999), but the pitch-angle scattering is mainly produced by gyroresonance interaction. Their analytical consideration showed that in a such specific model of turbulence the mean free path of charged particles is independent on rigidity. In the present paper we present preliminary results of Monte Carlo simulations of the mean free path for charged particles interacting with a finite amplitude turbulence being either the pure Alfvén waves or a mixture of isotropic fast mode waves and slab Alfveén waves.

2 Numerical modelling

Let us consider an infinite region of tenuous plasma with a uniform mean magnetic field along z-axis. It is perturbed with the described below propagating MHD waves. Test particles are injected into this turbulent magnetized plasma and their trajectories are followed by integrating particle equations of motion in space and momentum. By averaging over a large number of trajectories one derives the spatial diffusion coefficient along the mean magnetic field $\kappa_{||}$ and the respective mean free paths $\lambda = 3\kappa_{||}/v$. In the simulations we usually used 200 particles with the same initial velocity v_{ini} in an individual run.

2.1 Wave field models The turbulence is represented as a superposition of pure Alfvén waves or a mixture of isotropic fast mode and Alfvén waves. In the simulations, for any individual particle a separate set of wave field parameters is selected. As a result all averages taken over particles include also averaging over multiple magnetic field realizations. Generally, in the modelling we consider a superposition of 768 plane MHD waves. In the case of a mixture of MHD waves we involve in the simulations the same number of isotropicly distributed magnetosonic waves and Alfvén waves parallel to the mean magnetic field. Related to the i-th wave, the magnetic field fluctuation vector $\delta\vec{B}^{(i)}$ is given in the form:

$$\delta\vec{B}^{(i)} = \delta\vec{B}_o^{(i)} \sin(\vec{k}^{(i)} \cdot \vec{r} - \omega^{(i)} t + \Phi^{(i)}) \qquad . \tag{1}$$

The wave parameters - the wave vector k, the wave amplitude δB_o and the phase Φ- are drawn in a random manner from the Kolmogorov, $F(k) \propto k^{-5/3}$, wave spectrum. Waves vectors are expressed in units of the respective 'resonance' wave vector for an injected particles with momentum $p = p_o$, $k_{res} \equiv 2\pi/r_g(< B >, p_o)$ in the mean magnetic field $< B > \equiv < \sqrt{B_o^2 + \delta B^2}$ MHD. The wave amplitudes are drawn in a random manner so as to keep constant the models parameter δB:

$$[\sum_{i=1}^{768} (\delta B_o^{(i)})^2]^{1/2} \equiv \delta B, \tag{2}$$

The dispersion relations for the Alfvén waves, $\omega_A^2 = k_\|^2 V_A^2$, and the magnetosonic waves, $\omega_M^2 = k^2 V_A^2$, waves provide the respective ω parameters for a given wave mode. The sign of ω is defined by selecting the wave velocity V at, randomly, $\pm V_A$, but it is subject to a constraint that a number of waves moving in any direction is the same. In the simulations we adopt $V_A = 0.0005c$. We consider two types of wave spectra. First, a 'broad spectrum', where wave vectors are drown in a random manner from a broad wave vector range $k \in (k_{min} = 0.1 k_{res}^{min}, 10.0 k_{res}^{max})$, where k_{res}^{min} and k_{res}^{max} are, respectively, the minimum and the maximum *resonant* wave vector for the discussed particle velocity range. In the simulations we considered particle velocities ranging from nonrelativistic $v_{ini} = 0.05c$ up to relativistic $v_{ini} = 0.98c$ ones. For comparison we derived mean free paths for the 'narrow spectra', with wave vectors selected in a random manner from a narrow band near the resonant wave vector for a given initial particle velocity: $k \in (k_{min} = 0.1 k_{res}^{v_{ini}}, k_{max} = 10.0 k_{res}^{v_{ini}})$. Here $k_{res}^{v_{ini}}$ is the resonant wave vector for particles with the initial velocity v_{ini} . In the discussion below we consider four different turbulence fields:

- Alfvén waves with the broad spectrum,
- Alfvén waves with the narrow spectrum,
- Mixture of isotropic magnetosonic and slab Alfvén waves with the broad spectrum,
- Mixture of isotropic magnetosonic and slab Alfvén waves with the narrow spectrum,

3 Results of simulations and discussion

The derived mean free paths versus the particle velocities for the considered MHD turbulence models are presented in Fig. 1. In the figure one may observe that the simulated mean free paths slightly increase with increasing velocities for non-relativistic energies and for the relativistic particles a clear grow with energy is seen. That general trend does not depend on the turbulence model. However, for the MHD waves with narrow spectra the simulated mean free path values for the pure Alfvén waves are about five times larger than the ones for a mixture magnetosonic and Alfvén waves. The presence of compressive magnetic field components due to magnetosonic waves allows charged particles for interaction through the non-gyroresonance interaction called transit-time damping. It results in an effective pitch-angle scattering of particles at $\mu > \epsilon \equiv V_A/v$. The mean free path is determined then by gyroresonance interaction with the Alfvén waves at pitch angles less than ϵ (see Schlickeiser and Miller 1998). For MHD waves with broad spectra there are a few waves capable of resonantly interact with particles and the contribution of the transit-time damping and gyroresonance interaction to the mean free path becomes neglible. In such situation the nonresonant processes which does not distinguish the MHD wave modes will efficiently scatter particles.

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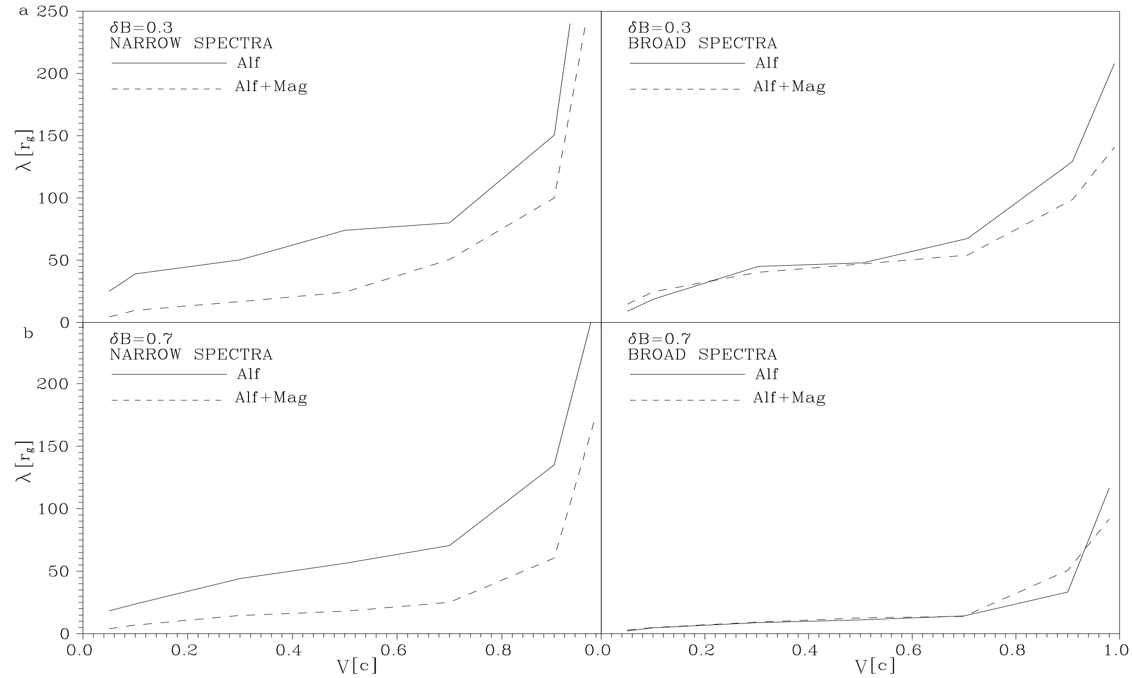

Figure 1: The simulated values of the mean free paths versus particle velocities for a mixture of magnetosonic and Alfvén waves (dashed line) and for pure Alfvén waves (solid line): a.) $\delta B = 0.3$, b.) $\delta B = 0.7$). The results for the narrow spectra are presented in left panels, and the ones for the broad spectra in right panels

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