Non-resonant pitch-angle scattering: comparison with the measurements for solar cosmic rays

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Abstract

Isotropic fast magnetosonic waves very efficiently scatter low-rigidity cosmic rays by the non-resonant process described in OG 3.2.45. Alfvén waves, which are likely to constitute a large part of the solar wind wave turbulence as well, are briefly shown here to give a negligible contribution to the pitch-angle scattering by this non-resonant process. The results of OG 3.2.45 can thus be used to fit the parallel mean free path obtained from measurements of solar cosmic rays as a function of the particles' rigidities, which is successfully done for rigidities ranging from 10^{-2} MV to 10^{5} MV.

1 Introduction

The quasilinear theory (Vedenov, Velikhov & Sagdeev 1962; Jokipii 1966; Schlickeiser & Miller 1998), which only includes the resonant waves in its description of the wave-particle interaction, can severely fail at predicting the pitch-angle scattering rate when at low rigidities, the resonance condition excludes a significant part of the turbulence spectrum. The excluded, low-frequency waves, which are responsible for the local variations of the field line direction, can provide the pitch-angle scattering missing in the quasilinear theory at pitch-angle cosine, μ, close to 0. In Ragot (1999a & b), we have calculated the non-resonant scattering resulting from a turbulence of isotropic fast magnetosonic waves. The solar wind wave turbulence, however, is likely to be composed of both fast magnetosonic and Alfvén waves which in a low-β plasma, are the less heavily damped. So, before we can — in the last part of this paper — fit the observations with the analytical results obtained in Ragot (1999a & b), we have to make sure that the other component of the turbulent wave spectrum does *not* produce dominant or similar effects by the non-resonant scattering process. We have argued in Ragot (1999a & b) that the slab Alfvén component of the spectrum, for reasons of symmetry, does not contribute to the non-resonant scattering. We defer to a further publication the precise demonstration of this statement, but will already give here the main point of the proof. We will also address the case of *oblique* Alfvén waves, and argue that these waves do *not* produce any significant scattering by the non-resonant scattering process *either*. In the rest of the paper we will present fits of the parallel mean free path as a function of the rigidity, deduced from measurements made in the heliosphere during solar events, and discuss the resulting parameters of the turbulence.

2 Contribution from slab and oblique Alfvén waves to the non-resonant pitch-angle scattering

In a turbulence of slab Alfvén waves, the fluctuating fields consist of transversal left- and right-hand polarized waves propagating parallel and anti-parallel to the homogeneous magnetic field $\vec{B}_0$. The polarization of the waves is circular. It follows that the integral (over $\vec{k}$) describing the variations of μ has an oscillatory integrand in $\exp[\pm i(\psi_{\vec{k}}+\varphi)]$, where $\psi_{\vec{k}} = \vec{k}.\vec{x}-\omega_{\vec{k}}t+\alpha_{\vec{k}}$ and φ is the gyrophase of the particle. As a consequence, averaging over the particle gyroperiod — the shortest timescale of the problem, see Ragot (1999a & b) — will just reduce the μ variation to a negligible contribution. The complete derivation will be published elsewhere. We come now to the case of oblique Alfvén waves, which is closer to the one of the oblique fast magnetosonic waves presented by Ragot (1999a & b).

When $\vec{k}$ is not along the main magnetic field $\vec{B}_0$, the Alfvén waves are linearly polarized waves with, if the inertia of the electrons is neglected, an electric field $\delta\vec{E}$ normal to $\vec{B}_0$, in the plane of $\vec{k}$ and $\vec{B}_0$. The magnetic field $\delta\vec{B}$ is normal to $\delta\vec{E}$ and $\vec{B}_0$. The different configuration of the magnetic field perturbation results here in an equation for the pitch-angle cosine μ of a form similar to equation (4) in OG 3.2.45, but where $\cos\psi^j_{\vec{k}}\cos(\varphi-\phi_{\vec{k}})$ substitutes for $\cos\psi^j_{\vec{k}}\sin(\varphi-\phi_{\vec{k}})$, $\phi_{\vec{k}}$ being the angle between $\vec{k}$ and the plane (x,z), with a z-axis along $\vec{B}_0$. The averaging of this equation over the particle gyroperiod will not permit to extract any constant term of significant amplitude, on the expected timescale of pitch-angle variation. Indeed, an expansion of $\cos\psi^j_{\vec{k}}\sin(\varphi-\phi_{\vec{k}})$ in Bessel functions only displays oscillatory terms in cos or $\sin n(\varphi-\phi_{\vec{k}})$ with n a strictly positive integer. This "shows" that the contribution from oblique Alfvén waves to the nonresonant pitch-angle scattering is also negligible.

3 Parallel mean free path of the solar cosmic rays: comparison of the theoretical predictions with the measurements

If the Alfvén waves, as argued in the previous section, do not produce any significant contribution to the pitch-angle scattering by the non-resonant effect, it means that the result obtained by Ragot (1999a & b) might already provide us with a reasonable description of the cosmic-rays scattering in the solar wind. We will now try to compare our theoretical predictions with the measurements.

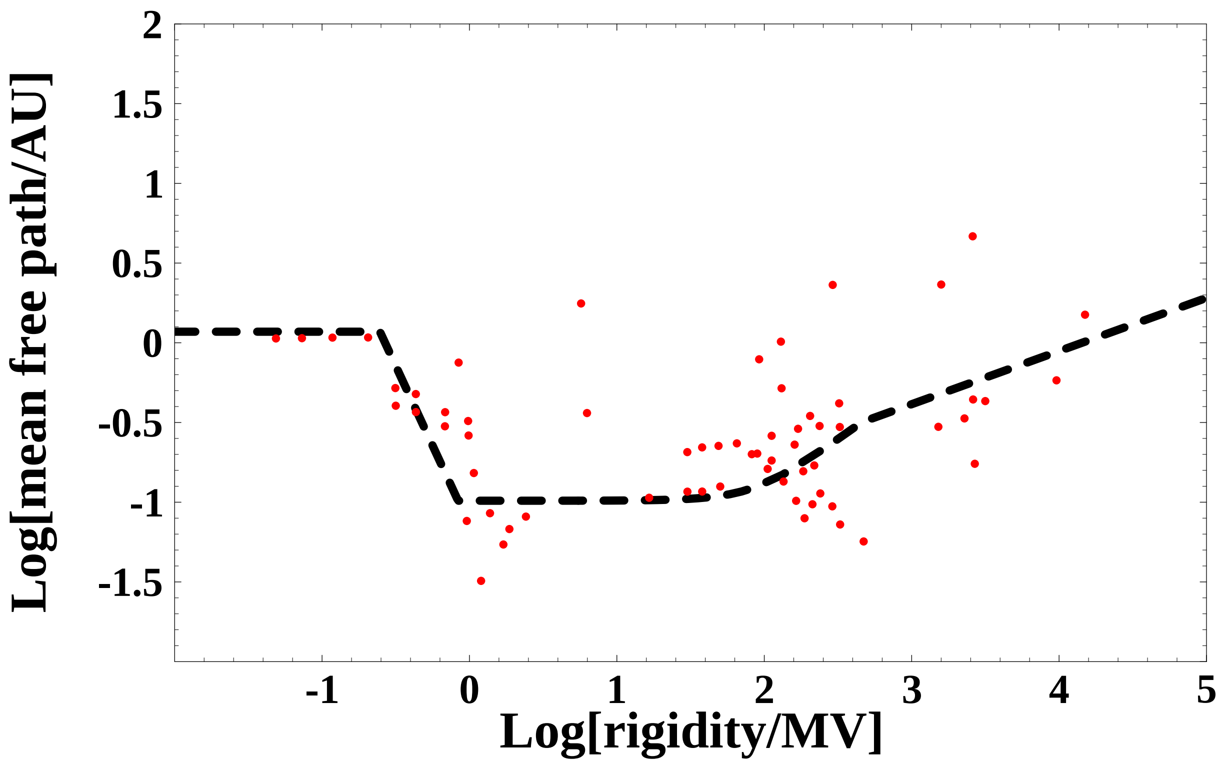

Figure 1: *Parallel mean free path versus particle rigidity, in logarithm, for various solar events. The dots represent parallel mean free paths derived above* $10\,MV$ *from proton observations, and below from electron observations, as published by Bieber et al. (1994). The theoretical curve in dashed line has been obtained with cut-off of the Alfvén and fast magnetosonic waves spectra at* $0.4k_c$ *and* $0.003k_c$*, respectively.* $\delta b_A = 0.1$, $\delta b_F = 0.13$ *and* $V_A = 10^{-4}c$. *The extension of the plateau at very low rigidities is directly related to the cut-off wavenumber of the Alfvén spectrum. This cut-off value is observed in the solar wind at about* k_c. *A value of* $0.4k_c$ *to produce the best fit presented here is reasonable, since the precise characteristics of the turbulence spectra might vary during a solar event from those of the "quiet" solar wind.*

The sensitivity of the mean free path to the characteristics of the fast magnetosonic waves spectrum — in particular, spectral index and cut-off wavenumber — and the fact that the data obtained from different solar events are often presented together, without reference to the distinct events, makes this comparison difficult. But we can already see from figure 1 that the theoretical curve globally fits the data points. The dispersion of the points around the theoretical curve presented on figure 1 should not be interpretated as uncertainty of the measurements, or inappropriateness of the theory to fit all the data. The data shown on figure 1 have been obtained from many different solar events. Their dispersion only indicates that the turbulence spectrum in the solar wind varies from one event to another. We have studied how the theoretical prediction is modified by variations of the turbulence spectrum, both fast magnetosonic and Alfvén component. We found a rather strong sensitivity of the theoretical prediction on the precise shape of the spectra. Even if the main features of the curve in figure 1 are preserved — *e.g.*, separation in three domains where the transit-time damping, non-resonant and gyroresonant interactions successively determine the parallel mean free path —, it is always possible the find a curve which will fit one subset of data points, keeping reasonable turbulence spectra. However, we cannot present here all the possible shapes of the curve "parallel mean free path versus particles' rigidity". We have to make some choice. We fit below one particular event, namely Nov 22, 1977, which looks very similar to Dec 27, 1977, and Apr 11, 1978 (see Dröge et al 1993; Beeck et al. 1987; Valdés-Galicia et al. 1988).

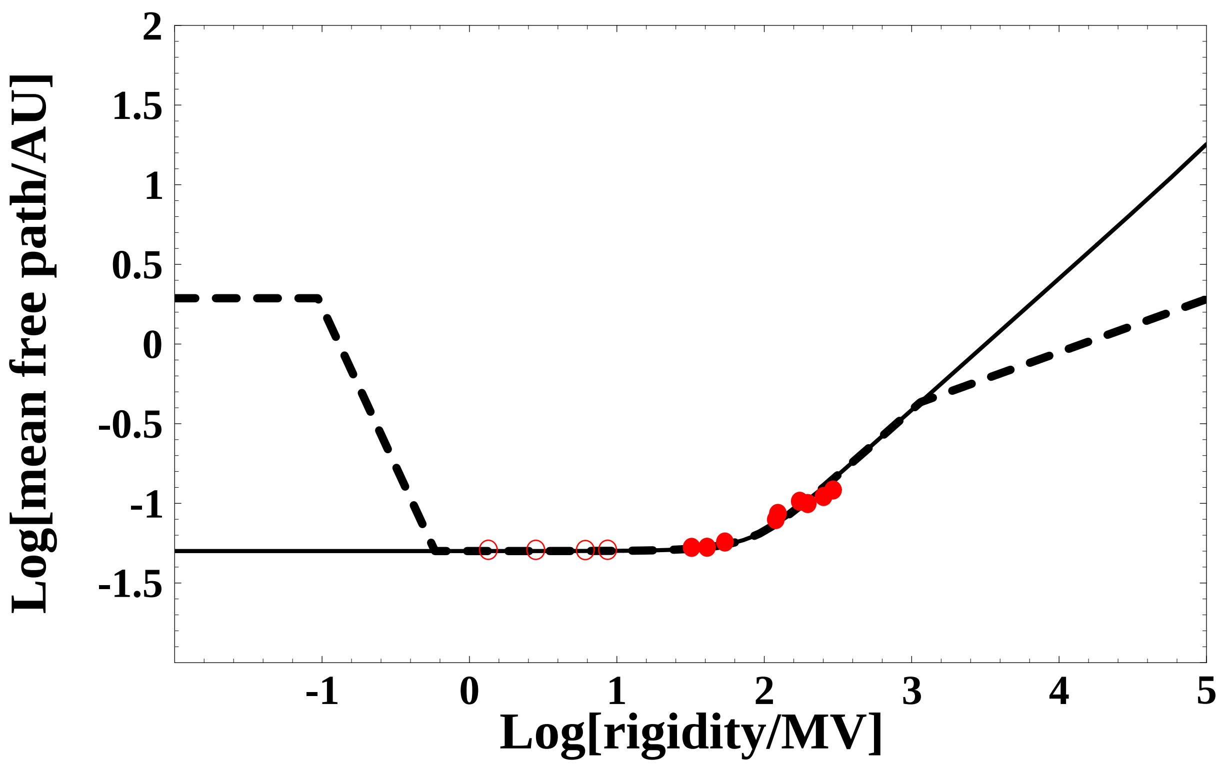

Figure 2: *Parallel mean free path versus particle rigidity, in logarithm, for the solar event of Nov 22, 1977 measured by Helios-1 (Beeck et al. 1987; Valdés-Galicia et al. 1988; Dröge et al 1993). The circles represent measurements for electrons, and the disks for protons. The theoretical curve remains valid on the whole range of rigidities for electrons. It only holds above about* $10\,MV$ *for protons, but all the data for protons are obtained above* $20\,MV$*, so that the theory is consistent with the observations presented in figures 1 and 2. The measurements, for this particular event, appear to be in the range where the non-resonant interaction with the fast magnetosonic waves dominates. The theoretical curve in thick dashed line is calculated with an Alfvén spectrum of Kolmogorov type up to* k_c*, and a fast mode wave spectrum damped above* $3.2 \times 10^{-3} k_c$*, with a spectral index of* 1.35 *below. In continuous line is plotted the mean free path resulting from the non-resonant interaction alone, assuming that the slowest scattering process occurs at small* μ*.*

All the measurements, for this particular event, appear to be in the range where the non-resonant interaction with the fast magnetosonic waves dominates. It would be necessary, in order to validate the theory and obtain the whole information on the turbulence spectra, to have data for single events on a broader range of rigidities, spanning the intervales where the transit-time damping (below 1 MV) and gyroresonant (above 10^3 MV) interactions determine the parallel mean free path.

Still, an important conclusion can be drawn from this fit: at least for the particular events shown in the paper by Dröge (1993), the scattering rate and resulting $\lambda_{||}$ are consistent with a spectrum of fast magnetosonic waves cut off (or strongly steepening) at a "small" fraction ($\sim 10^{-2}$) of k_c. Such a sharp decrease of spectral power well below k_c cannot result from thermal damping. It could, however, very well be explained by the resonant, transit-time damping. Indeed, Ragot & Schlickeiser (1998a & b) have shown that the fast mode branch very efficiently accelerates low-energy cosmic rays, and that the fast magnetosonic waves ($k < k_c$), alone, already produce a very strong acceleration. Moreover, the fast magnetosonic waves responsible for the main part of the acceleration have wavenumbers precisely in the range that appears to be damped in the solar wind on Nov 22, 1977, on the path of the observed cosmic rays. We think that the fast magnetosonic waves with k between $10^{-2}k_c$ and k_c might have been present closer to the sun, but have been damped before propagating outward in the solar wind, while accelerating low-energy cosmic rays. This in no case means that everywhere in the solar wind, the fast magnetosonic waves are damped above $10^{-2}k_c$, but that whenever a large number of low-rigidity, resonant cosmic rays are observed, there exists the possibility that these particles, together with the ones that have propagated downward, have damped the fast magnetosonic wave spectrum at relatively low wavenumbers.

Acknowledgements: This work was performed while the author held a National Research Council - NASA / GSFC Research Associateship. B.R.R. gratefully acknowledges interesting discussions with R. Schlickeiser, A. Roberts, M. Lee and F. Jones.

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