Nonresonant cross-field diffusion of 100 keV to 2 MeV protons in interplanetary space

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The cross-field diffusion of charged particles in a magnetized plasma in the presence of electric and/or magnetic field fluctuations is known to play an important role in many situations and space plasma regions (see [1-6]). In the absence of a fully self-consistent and predictive theory for the cross-field diffusion, it is generally assumed that the diffusion is close to the so-called Bohm limit. The value of Bohm diffusion coefficient, D_B, leads to a mean free path of the charged particles equal to the gyroradius, which is thought to be the lowest possible value for isotropic turbulence [7-9].

In this paper, the nonresonant cross-field diffusion of energetic charged particles resulting from their interactions with magnetic decreases (MDs) is investigated. Considered particle energies are from 100 keV to 2 MeV. The main effect of a charged particle MD interaction is the cross-field diffusion due to particle guiding center displacements (see, e.g. [10-12]).

MDs are depletions in the interplanetary magnetic field (IMF) magnitude convected by the solar wind. They are pressure balance structures where the magnetic pressure decreases are supplanted by plasma thermal pressure increases [13]. MD sizes range from a few to thousands of proton gyroradii [14]. They are observed at different heliocentric distances and in both low and high heliospheric latitudes [10, 13, 14].

We perform Monte Carlo simulations of the interaction of energetic protons with the MDs using a geometrical model [10-12] and determine the diffusion coefficient as a function of proton energy. Here we select three periods for analyses, observed by Ulysses. During the first period, interplanetary magnetic field data were obtained at the south pole of the heliosphere (≈-80°), for the days 242-268 of 1994 and were first discussed in Ref. [15]. For this high latitude period, 129 MDs were identified. The two other periods were obtained for low heliospheric latitudes. For the period between days 109 and 110 of 1992 and a latitude of ≈ 9.6°, associated with an interplanetary shock, 137 MDs were observed. This gives a MD occurrence rate ≈ 14 times the rate for high latitudes. For the period between days 364 and 365 of 1992, at a latitude of 22.6°, associated with a corotating interaction region (CIR), 118 MDs were observed. This gives a similar rate of occurrence as previous event. The fact that MDs occurs more frequently at low heliospheric latitudes than for high latitudes has been previously observed [13].

For the three periods, a distribuition was obtained as a function of the MD sizes (*dm*) and of the ratio between the magnetic field intensities within the decrease (B_{MD}) and outside region (B_0), ΔB. Sizes of MDs were obtained by multiplying their temporal duration by the observed solar wind speed. The obtained distributions (histograms) were fitted using Monte Carlo method, as described by [11].

To estimate the displacement, λ, of the particle guiding center across MDs, we use a geometrical, idealized and mathematically treatable case. Figures 1 (a) and 1 (b) ilustrates the displacement suffered by the gyroradius center when particle interacts with an MD [10,11].

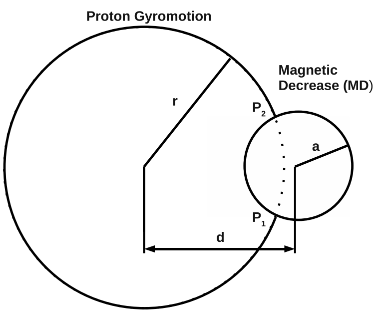

Figure 1 (a) Geometry of the interaction of a charged particle of gyroradius r and a MD of radius a [10].

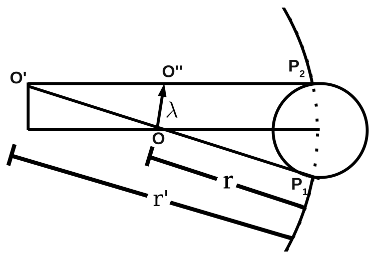

Figure 1 (b) Cross-field displacement of the guiding center of a charged particle after interacting with a MD [10].

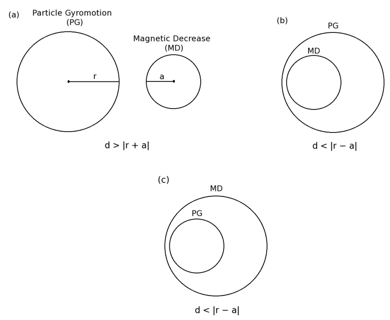

Figure 1 (c) Situations when the particle MD interaction is not possible, depending on the size of MD (a), the gyroradius of the particle (r), and the impact parameter (d).

To calculate λ, resulting from the particle interactions with ''n'' number of MDs we solve Eq. (3) of Reference [11] ''n'' times and account the displacement for the several interactions. In the present calculations, we investigate interactions with 100 and 200 MDs (n=100 and 200, respectively). We consider B_0 = 1.2 nT. The gyroradius *r* is also constant, depending only on the particle's energy. Statistically, the MD radius, *a=1/2 dm,* and ΔB, were taken from a Monte Carlo representation of the fitting equations for the distributions obtained from the data. The impact parameter *d* is randomly selected in the range where the interaction can take place $(|r - a| < d < |r + a|$. Interactions can occur at any angle θ of particle's trajectory in space $(0 \leq \theta \leq 2\pi)$. Results shown here were obtained for particles with 45° pitch angle. Figure 2 shows the values of λ, as a function of ion perpendicular energy, for the high heliospheric latitude. Figure 3 shows the results for the low heliospheric latitude events. In both figures, the blue circles represent λ and the red squares are the average of 10 values of λ, for each energy. In Panel A we use interactions with 100 MDs and in Panel B, 200 MDs.

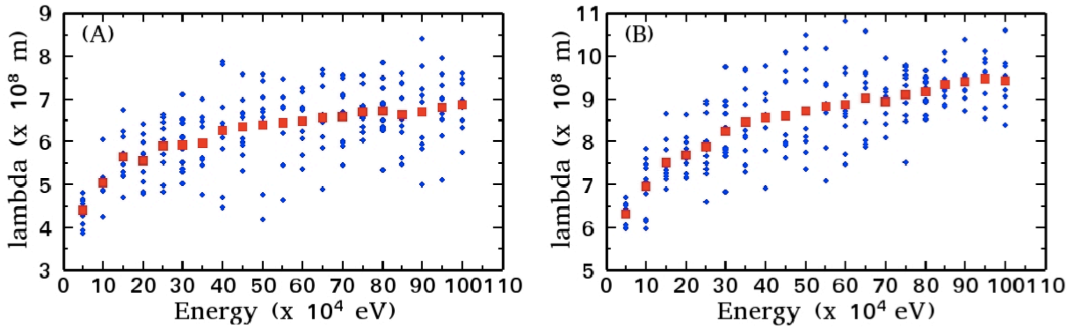

Figure 2. Values of λ, as a function of ion perpendicular energy, for the high heliospheric latitude event. See text for explanation.

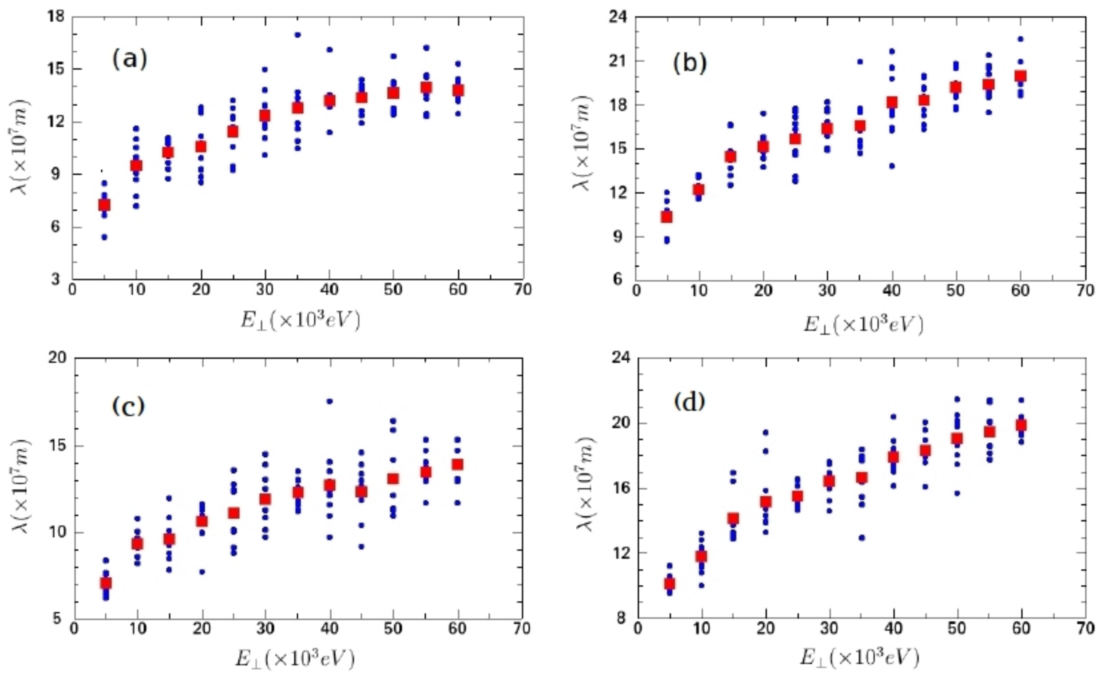

Figure 3. Values of λ, as a function of ion perpendicular energy, for the low heliospheric latitude events: (a) and (b) for shock event and (c) and (d) for CIR event. See text for explanation.

The maximum diffusion distance obtained for the high heliospheric latitude region is around 3 times larger than the ones founded for the two low heliospheric latitude region, for particles with energies between 10 to 120 keV. The size of MDs in low latitude regions are smaller than for the ones in high latitude regions. In that case, particles with higher energies will weakly interact with MDs. It explains the different scales in Figures 2 and 3.

In order to compare diffusion in different regions, we define a diffusion coefficient as $D_{\perp} = \frac{<\lambda^2>}{\Delta t}$, where Δt is the time between ion MD encounters. Δt depends on the distance between the MDs given by the data and on the energy of the ions.

Preliminary results, not shown here, indicates that the cross-field diffusion coefficient, normalized by Bohm diffusion, can lead to a rapid (> $0.1D_{Bohm}$) cross-field diffusion of ~1 MeV protons. Cross-field diffusion coefficients for low heliospheric latitudes are larger than that for high latitudes. The general idea of nonresonant wave-particle interactions may have applications to astrophysical and laboratory plasmas as well.

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