SH 1.6.05

Scattering mean free path of energetic protons in the Heliosphere

G. Erdõs[1], A. Balogh[2], and J. Kóta[3]

[1] *KFKI Research Institute for Particle and Nuclear Physics, 1525 Budapest, POB 49, Hungary*

[2] *The Blackett Laboratory, Imperial College, London SW7 2BZ, U.K.*

[3] *Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA*

Abstract

The effect of magnetic field fluctuations on charged particle propagation is investigated. Quasi-linear theory is used to deduce the diffusion coefficient of energetic particles from magnetic field data measured by Ulysses at high heliographic latitude. The λ_{QLT} scattering mean free path of 1 MeV protons is determined along one complete off-ecliptic orbit of Ulysses. It is shown that the difference between the fluctuations in the high and in the low speed solar wind results smaller λ_{QLT} in the polar regions than near the ecliptic. The mean free path increases by the R radial distance from the Sun, which can be approximated by the power function $\lambda_{QLT} \sim R^{1.3}$.

1 Introduction:

The propagation of the energetic charged particles through the solar system is affected by the heliospheric magnetic field. The problem is obviously three dimensional in nature, however only recently, Ulysses spacecraft made the deep off-ecliptic regions available for in situ studies. On large scale, the magnetic field lines well follow the theoretical Parker spiral at high latitude, although, some deviations in the azimuth direction were established (Forsyth et al., 1996). It was also considered that the magnetic field lines may bend toward the ecliptic plane (Fisk, 1996), this question however is still debated. On small scale, the fluctuations of the field is responsible for the diffusion of particles. Ulysses has measured large amplitude waves in the polar regions (Smith et al., 1995), which was predicted by theoretical considerations (Jokipii and Kóta, 1989). The scattering of particles by these waves are likely to explain that Ulysses has measured considerably smaller particle flux at high latitude than expected (McKibben et al., 1996).

The derivation of diffusion coefficient from magnetic field fluctuations is still an open question. The problem is that the interaction between particles and waves which scatter them is highly nonlinear, making difficult both to calculate the process and to identify and to characterize the fluctuation modes relevant for scattering. This latter problem is mainly related to the inadequate knowledge of the magnetic field from a single spacecraft observation. Up to now the quasi-linear theory (QLT) is the most widely used model to calculate the diffusion coefficient. That theory, however, has difficulties to give quantitative answers, in particular the scattering mean free path of particles calculated from quasi-linear theory is about an order of magnitude smaller than that determined from particle flux observations (Palmer, 1982).

Recently Ulysses has completed the first off-ecliptic orbit around the Sun, which enables us to study the three dimensional structure of Heliosphere. It was shown that two types of solar wind exists in the Heliosphere (Goldstein et al., 1996). The velocity of the solar wind, originating from the coronal hole at high latitude is about twice as large as the velocity of slow wind originating closer to the equator of the Sun. The characteristics of the high speed and the slow speed solar wind plasma are remarkably different, which also includes the fluctuations of the magnetic field (Holbury et al., 1996).

The purpose of this paper is the quantitative investigation how the fluctuations of the magnetic field are related to particle scattering. We use QLT approximation to determine the parallel mean tree path (λ_{QLT}) of 1 MeV protons from the magnetic field data observed by Ulysses during the first off-ecliptic orbit. Due to the limitations of QLT above, the values of λ_{QLT} are probably underestimated, as was experienced earlier by in-ecliptic studies. However, the mean free path shows characteristic variations along the orbit of Ulysses, in particular, the dependence of λ_{QLT} on heliographic latitude and on distance from the Sun is established. The implications for the modulation of cosmic rays are discussed.

2 Method:

According to the quasi-linear theory (Jokipii, 1966), the scattering mean free path is

$$\lambda_{QLT} = 3 \cdot r_G^2 \cdot \int_0^1 \frac{\mu(1-\mu^2)}{P_{xx}+P_{yy}} d\mu \qquad (1)$$

where r_G is the giroradius of particles, μ is the cosine of pitch angle. The denominator is the relative power of magnetic field fluctuations at resonant wave number $k = \omega_G/\mu v$ in the plane perpendicular to the mean field direction:

$$P_{xx} + P_{yy} = \int_{-\infty}^{\infty} \frac{< B_x(z)B_x(z+z') + B_y(z)B_y(z+z') >}{B^2} \cdot \exp(i\frac{\omega_G z'}{\mu v})dz' \qquad (2)$$

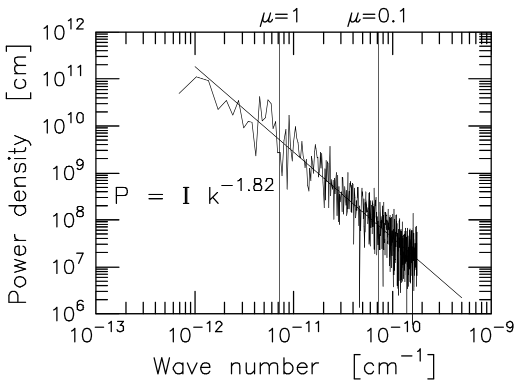

Figure 1 Power spectrum of magnetic field fluctuations.

We have calculated the power spectra on 1024 field vectors averaged by Δt = 1 minute. Time step was converted to distance $\Delta z = w_z \Delta t$ along the main magnetic field direction (z axis), which was determined by averaging the field vectors over the whole 1024 minute time interval (w_z is the velocity component of the solar wind in the mean field direction). According to Ulysses measurements, for a wide range of wave numbers the power spectra can be well approximated by a power low:

$$P(k) = I \cdot k^{-q} \qquad (3)$$

Substituting (3) into (2) and (1), we arrive at

$$\lambda_{QLT} = \frac{3 \cdot r_G^{2-q}}{I_{xx}+I_{yy}} \cdot \int_0^1 \mu^{1-q}(1-\mu^2)d\mu \qquad (4)$$

where the integral is trivial and convergent, if the spectral exponent $q < 2$. Figure 1 shows typical spectrum (measured on 1st of January, 1994), together with the result of power low fit according to (3). The vertical lines mark the wave number range which is resonant with 1 MeV protons having pitch cosine $0.1 < \mu < 1$. All through the paper, we have calculated the λ_{QLT} mean free path for 1 MeV protons; that energy was selected because the resonant wave number range of 1 MeV protons is reasonably well inside the determined spectra for the whole orbit of Ulysses.

3 Observations:

We have calculated the scattering mean free path of 1 MeV protons from magnetic field fluctuation spectra of about 16 hours time intervals, measured by Ulysses during the first off-ecliptic orbit, i.e., from the Jupiter encounter at February, 1992 to the aphelion at early 1998. Figure 2 shows the mean free path λ_{QLT} as determined on the basis of equation (4) (second line from the top) and the spectral exponent q (third line).The top and bottom lines show the magnetic field magnitude and the velocity of the solar wind (measured by SWOOPS instrument, courtesy of McComas), respectively. The top horizontal scale displays the orbital data of Ulysses.

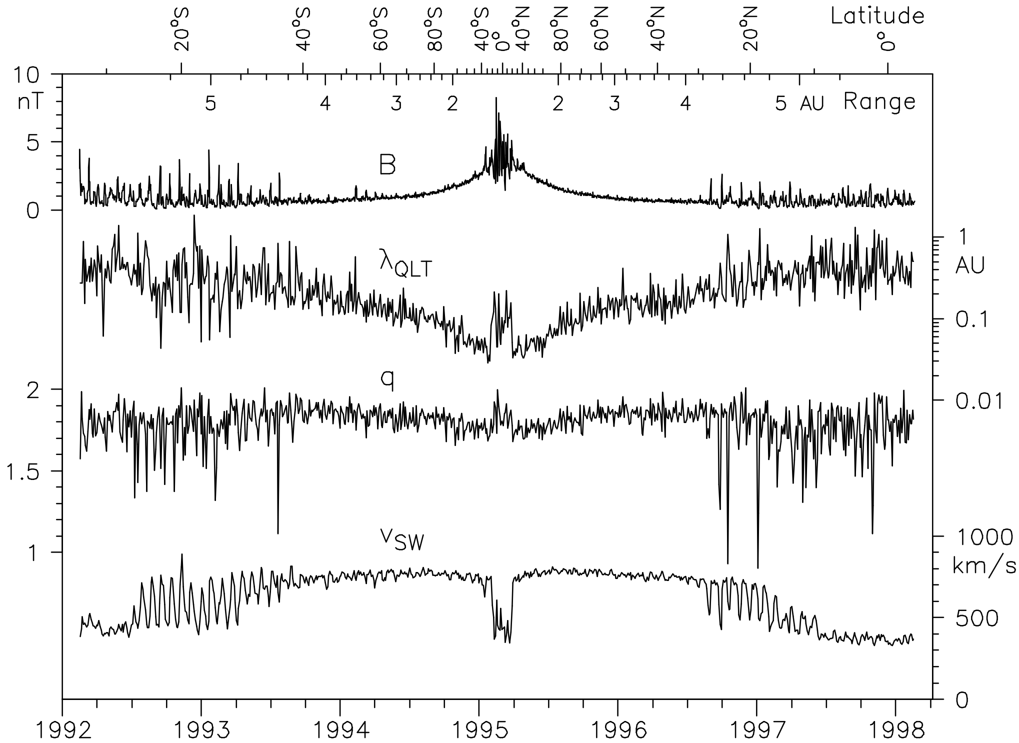

Figure 2 Magnetic field (B), scattering mean free path (**λ_{QLT}**), spectral index (q), and velocity of solar wind (v_{SW}), measured by ULYSSES during the first off-ecliptic orbit.

The velocity of the solar wind clearly shows the corotating interaction regions (CIR), observed by Ulysses for about a year long time interval in 1992-93 (at heliographic latitude 10^0-40^0 south) and for a shorter time in 1996-97 (30^0-10^0 north). The CIRs also affect the spectral index q and the mean free path λ_{QLT}, which values are highly variable during those intervals. The variations are consistent with 26 day periodicity, however this question will be investigated in detail in a future paper only. In the slow solar wind (first half of 1992; equatorial crossing in 1995; and second half of 1997) the values of mean free path and the spectral index also scatter, explainable with transient events (shocks, CMEs) occurring frequently in the streamer belt. As a contrast, in the high speed solar wind λ_{QLT} and q are relatively quiet, with long time scale trends, apparently associated with orbital characteristics of Ulysses. A remarkable feature of Figure 2 is that all the lines are close to symmetric with respect to the perihelion passage at early 1995.

We have investigated the symmetry further by plotting the λ_{QLT} scattering mean free path, as a function of the R radial distance of Ulysses from the Sun. In Figure 3 data from the southern hemisphere (1992-95) are superimposed on the data of the northern hemisphere (1995-98); the two lines match each other reasonably well, in spite of the fact that Ulysses has sampled the two hemispheres at different phases of the solar sunspot cycle. This suggests that no significant time variations occurred in the mean free path of 1 MeV protons during the time interval covered. In the high speed solar wind we may approximate the radial dependence of the mean free path by a power law $\lambda_{QLT} \sim R^{1.3}$.

We have normalized the mean free path to R = 1 AU by the power law above and plotted in Figure 4 as a function of the heliographic latitude. The tick line from left to right shows the results of the fast latitude scan section of the orbit from the southern polar pass to the northern one. There is no considerable variation by latitude beyond the streamer belt, i.e., outside the range of $\pm 30^0$ latitude. In the streamer belt (slow solar wind), the value of λ_{QLT} is about 2-3 times larger than in the polar regions (fast solar wind). This tendency is also present in the "slow latitude scan" (from Jupiter encounter to southern polar pass, and from northern polar pass to aphelion), although the scatter of data points are much larger (thin line in Figure 4).

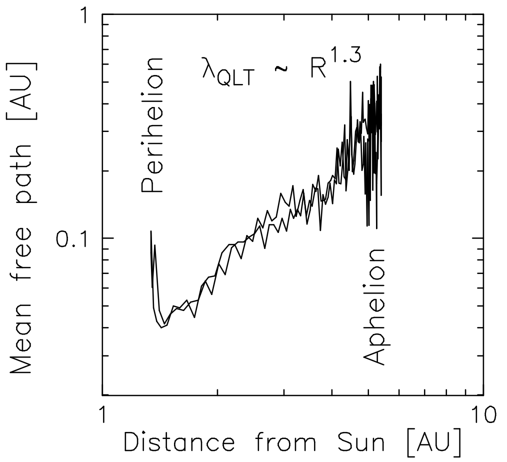

Figure 3 Radial dependence of λ_{QLT}.

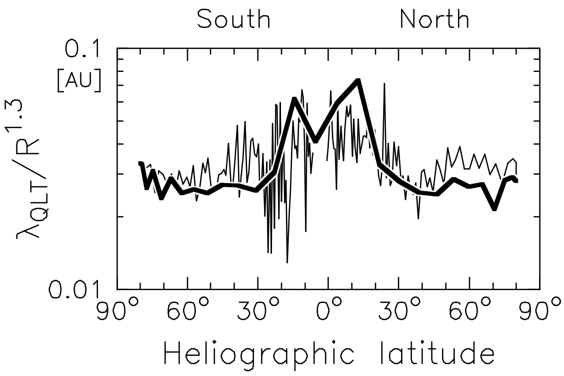

Figure 4 Latitudinal dependence of λ_{QLT}.

4 Discussion:

The limitation of the quasi-linear theory makes the absolute value of the mean free path questionable but, the radial, latitudinal and time (solar cycle) dependence of λ_{QLT} may give some constraints on the models of cosmic ray modulation. The increase of λ_{QLT} by radial distance looks as a giroradius effect. However, the QLT mean free path is practically independent of r_G (see equation 4), a more likely interpretation is that due to turbulence in the solar wind, the fluctuations decay as the plasma travels to larger distance. In this way, we may also explain the smaller mean free path observed in the polar regions, since for a given radial distance, the travel time of fast solar wind plasma is much smaller (by a factor of about 2) than that of the slow wind.

The λ_{QLT} did not show a direct dependence on the phase of solar cycle. However, the latitudinal extent of the fast solar wind, where a smaller mean free path is likely to exist, changes with the cycle which may contribute to the 11 year modulation of charged particles. Note, that this would also imply a difference between even and odd cycles (22 year modulation), since those particles entering the inner Heliosphere from the poles in one cycle should be more sensitive to the latitudinal extent of the polar coronal holes.

Acknowledgment: This work was supported by Hungarian national research grant OTKA T-30078.

References

Fisk, L.A. 1996, J. Geophys. Res. 101, 15547

Firsyth, R.J., Balogh, A., Holbury, T.S., Erdõs, G., Smith, E.J., Burton, M.E. 1996, A&A 316, 295

Goldstein, B.E., Neugebauer, M., Phillips, J.L., Bame, S., Gosling, J.T., McComas, D., Wang, Y.-M., Sheely, N.R., Suess, S.T. 1996, A&A 316, 296

Holbury, T.S., Balogh, A., Forsyth, R.J., Smith, E.J. 1996, A&A 316, 333

Jokipii, J.R. 1966, ApJ 146, 480

Jokipii, J.R. and Kóta, J. 1989, Geophys. Res. Lett. 16, 1

McKibben, R.B., Connell, J.J., Lopate, C., Simpson, J.A., Zhang, M. 1996, A&A 316, 547

Palmer, I.D. 1982, Rev. Geophys. 20, 335

Smith, E.J., Balogh, A., Neugebauer, M.,McComas, D. 1995, Geophys. Res Lett. 22, 3381