Perpendicular diffusion and drift of solar energetic particles in heliospheric magnetic fields

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Abstract

We present evidence for large perpendicular diffusive flows of solar energetic particles. Using anisotropy measurements of 40-90 MeV protons from the July 14th, 2000 event obtained by HET on Ulysses, we find periods of first order anisotropy directed at significant angles to the local magnetic field, which can only be satisfactorily explained by perpendicular diffusion. A large $\kappa_\perp/\kappa_{||}$ of 0.25 is derived. We also find that the anisotropy is unaffected by the polarity of magnetic field. This puts an upper limit of $\kappa_A/\kappa_\perp < 0.17$ on the particle drift. The observation suggests that perpendicular diffusion is important to the transport of solar energetic particles in interplanetary magnetic fields.

1. Introduction

Diffusion and drift of energetic charged particles in turbulent heliospheric magnetic fields are important processes that govern variety of phenomena such as the modulation of cosmic rays, interplanetary propagation of solar energetic particles (SEP), particle acceleration by shock waves. Both effects of particle transport are contained in the diffusion tensor $\kappa_{ij} = \kappa_\perp \delta_{ij} + (\kappa_{||} - \kappa_\perp) b_i b_j + \epsilon_{ijk} b_k \kappa_A$, where ϵ_{ijk} is the totally antisymmetric Levi-Civita epsilon and b_i is a vector component of magnetic field direction. Although $\kappa_{||}$ is reasonably well determined [1], our understanding of $\kappa_\perp$ is still unclear. Assumptions of different turbulence often result in very different values for the $\kappa_\perp/\kappa_{||}$ ratio, which ranges from $< 10^{-5}$ by hard sphere scattering to $\sim 10^{-1}$ through field line random walk [2]. While the most dominant idea based on the focused transport theory of SEP propagation completely neglects the cross-field transport [6], several recent observations indicate that perpendicular transport can be important [4,8]. Similar requirement has been established by observations of cosmic ray modulation [3,5].

This paper presents an analysis of anisotropy measurements of 40-90 MeV protons from the July 14 (day 196), 2000 SEP event. The analysis provides

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compelling evidence for a large perpendicular diffusion flow at Ulysses in the early phase of the event. A value of the $\kappa_\perp/\kappa_{||}$ ratio is derived for this event. An upper limit also is placed on the $\kappa_A/\kappa_\perp$ ratio.

2. Observations and Analysis

Ulysses is a spinning spacecraft at ∼12 rpm. The High Energy Telescope (HET) is mounted on the platform with its axis perpendicular in the spin axis. Count rate measurements in H45S channel (40-92 MeV protons) are divided into 8 sectors (See [7] for details). We fit the H45S sectored count rates with a sum of harmonics up to the second order to derive the anisotropy of the particle flux.

Figure 1 shows the obtained anisotropy parameters together with Ulysses measurements of magnetic field direction. On July 14 of 2000, an X-5 solar flare occurred on the sun at 22°N heliographic latitude near central meridian from Earth. A very fast halo CME was observed and it was detected by many near-Earth spacecraft one day later. At that time Ulysses was at 3.17 AU from the sun, 62°S heliographic latitude and $\sim 180°$ away from the flare in longitude [8].

A significant first order anisotropy was observed as soon as the count rate exceeds the statistical threshold for meaningful determination of anisotropy. It represents a particle flow in the spacecraft reference frame.

The azimuth angle of the first order anisotropy (Φ_1), for most of the time during the phase of increasing flux, is not along the magnetic field direction projected onto the scan plane. At first, it tries to follow the changing magnetic field direction while the difference gets bigger and bigger. Once the azimuth angle of the magnetic field reaches a certain value, the anisotropy direction swings in the opposite way. The anisotropy direction crosses the magnetic field direction around 1100UT on day 197, while the magnitude of the first order anisotropy reaches a brief minimum. In the time period 1200−2400 UT on day 197, the first order anisotropy becomes almost perpendicular to the magnetic field direction. This observation of cross-field anisotropy indicates that the particle flow cannot entirely come from particle streaming along the magnetic field lines. After 0200UT, day 198, the cross-field anisotropy ceases while the particle intensity decays slowly.

Perpendicular particle flow can come from three possible sources: the Compton-Getting effect, particle drift, and diffusion. Table 1 lists their expected magnitude or direction for the observed condition of the event. The Compton-Getting effect is ruled out because it cannot produce the observed magnitude of the anisotropy. The anisotropy from the drift effect should depend on the magnetic field direction; lack of change in anisotropy direction at 0000UT on day 197 when the magnetic field switches polarity rules out the possibility of drift anisotropy. Therefore, only the diffusion is left for explanation of the observation.

Assuming that the anisotropy is due entirely to the diffusion and assuming

Table 1. Possible contribution to perpendicular anisotropy. V_{sw} – solar wind speed, v – particle speed, γ – particle spectra index, $\hat{\mathbf{b}}$ – magnetic field direction, κ_S – symmetric part of the diffusion tensor.

Source	Formula	Expectation
Compton-Getting effect	$\mathbf{A}_{1,CG} = 2(\gamma+1)\frac{V_{sw}}{v}$	$A_{1,CG} < 0.04$ for $V_{sw} = 650$ km/s, $\gamma < 2$, 50 MeV protons
Drift	$\mathbf{A}_{1,drift} = \frac{3\kappa_A \hat{\mathbf{b}} \times \nabla \ln f}{v}$	$\mathbf{A}_{1,drift}$ changes its direction with magnetic field polarity
Diffusion	$\mathbf{A}_{1,diff} = \frac{3\kappa_S \cdot \nabla \ln f}{v}$	

that particle density gradient does not change rapidly with magnetic field direction, we can calculate the anisotropy direction and magnitude projected onto the scan plane of the instrument using the formula of diffusion anisotropy in Table 1. The curves in the Φ_1 and A_1 panels of Figure 1 are the calculation results with a $\kappa_\perp/\kappa_{||} = 0.25$, a parallel mean free path to particle gradient scale ratio $\lambda_{||}/L$ of 1.0 and a fixed direction of the particle gradient. The features in variations of both Φ_1 and A_1 between 0600−2400UT on day 197 are reproduced in the diffusion calculation result. At around 1100UT, the anisotropy is smallest because the diffusive flow happens to be nearly perpendicular to the scan plane of the instrument. In the early phase of the event, the observed anisotropy direction is somewhere between the diffusion calculation and magnetic field direction from the sun, indicating that both particle streaming and perpendicular diffusion are present there. After 0200UT, day 198, big discrepancy is shown in the anisotropy magnitude, probably because the anisotropy mainly comes from parallel transport due to change of particle gradient after the maximum intensity.

The lack of change in anisotropy direction at 0000UT on day 197 when the magnetic field switches its polarity has allowed us to put an upper limit on particle drift. Using the formulae in Table 1, we derive from the error bar calculation of anisotropy direction that $\kappa_A/\kappa_\perp < 0.17$.

3. Summary

From the above analysis of the anisotropy measurements of 40-92 MeV solar energetic proton from the July 14, 2000 event, we have derived a large $\kappa_\perp/\kappa_{||}$ ratio of 0.25. The observation has clearly established the need that perpendicular transport must be considered even in the early phase of SEP events. The observed large $\kappa_\perp/\kappa_{||}$ ratio and small $\kappa_A/\kappa_\perp$ ratio provide a tough challenge to the theory of particle transport in turbulent magnetic fields.

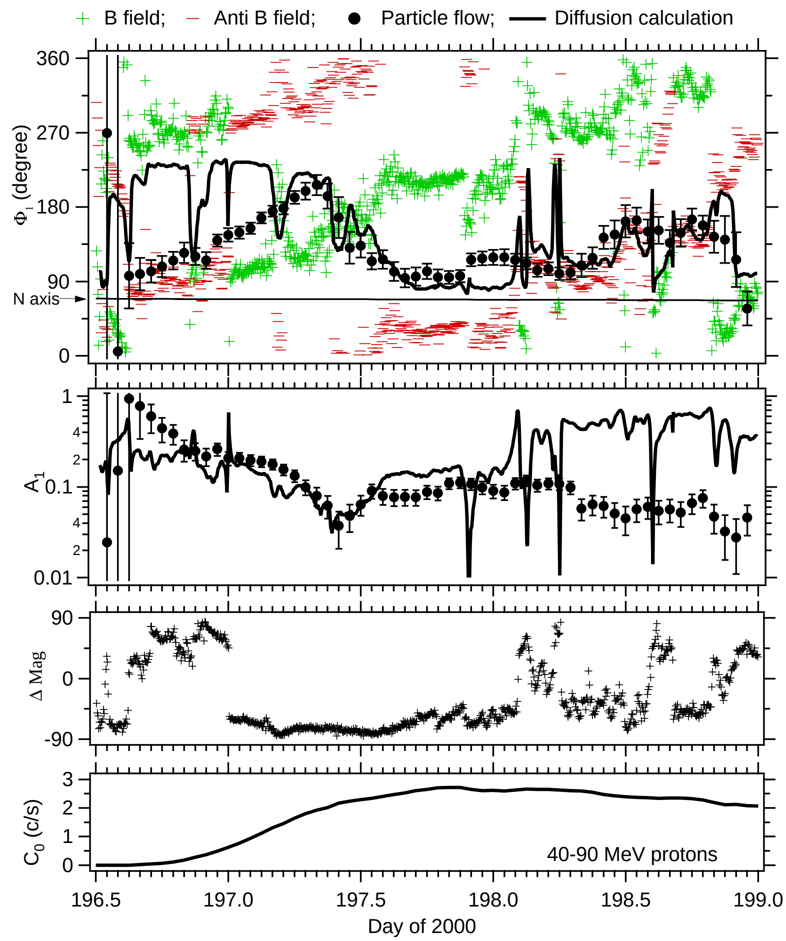

Fig. 1. Fitting parameters to the Ulysses HET sector H45 hourly average counting rates together with 5-min average magnetic field direction. The fitting function is $C_0[1 + A_1 \cos(\phi - \Phi_1) + A_2 \cos 2(\phi - \Phi_2)]$. Δ is the angle of magnetic field to the scan plane.

4. References

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