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PERPENDICULAR TRANSPORT OF LOW-ENERGY COROTATING INTERACTION REGION–ASSOCIATED NUCLEI

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ABSTRACT

We present compelling observational evidence for substantial transport of energetic charged particles across the local average magnetic field. Using data from the STEP/EPACT instrument on board the *Wind* spacecraft, we find that during three intense corotating interaction region (CIR) events, for periods greater than 12 hr, the observed anisotropy of the particle intensity at 1 AU is often directed at a significant angle to the measured magnetic field direction, which implies significant transport across the local magnetic field. A simple diffusion model is found to fit the three events very well with a large inferred $\kappa_\perp/\kappa_\parallel$. For example, for 80–154 keV nucleon^{-1} helium, we find that $\kappa_\perp/\kappa_\parallel = 1.47 \pm 0.07$, $\kappa_\perp/\kappa_\parallel = 0.13 \pm 0.02$, and $\kappa_\perp/\kappa_\parallel = 0.45 \pm 0.05$ for the most intense periods of the three events. We believe that this is the first direct, quantitative measurement in space of large cross-field particle transport, utilizing simultaneous measurements of the streaming particle flux, the solar wind velocity and the magnetic field direction.

Subject headings: cosmic rays — diffusion — interplanetary medium — magnetic fields — solar wind

1. INTRODUCTION

The transport of energetic charged particles through a turbulent or irregular magnetic field is a subject of considerable interest to the physics of energetic particles in space and the physics of collisionless plasmas. Although there is considerable literature (both theoretical and observational) concerning transport parallel to the average magnetic field (Jokipii 1971; Smith, Bieber, & Matthaeus 1990), perpendicular transport remains much more poorly understood and studied. This circumstance occurs despite the fact that in many important situations (e.g., shock acceleration, solar modulation of Galactic cosmic rays, and escape of cosmic rays from the Galaxy) the average magnetic field is perpendicular to the direction of transport, so understanding perpendicular transport is a problem of fundamental importance.

The simplest picture of transport approximates the small-scale interaction of fast charged particles with turbulent magnetic field with a scattering time, τ_c, which for particles having a speed w gives rise to a parallel mean free path, $\lambda_\parallel = w\tau_c$, and parallel diffusion coefficient, $\kappa_\parallel = w\lambda_\parallel/3$. If r_c is the gyroradius in the (smoothly varying) average or background magnetic field, the analysis then yields a perpendicular coefficient, $\kappa_\perp = \kappa_\parallel/[I + (\lambda_\parallel/r_c)^2]$, which is generally much less than $\kappa_\parallel$. For example, the mean free path of 1 MeV nucleon^{-1} ions near 1 AU in the solar wind is typically taken to be ≥0.1 AU. This yields a value of $\kappa_\perp/\kappa_\parallel \leq 10^{-5}$, which is negligible in many cases.

However, a more sophisticated analysis of particle motion in a turbulent magnetic field, using quasi-linear theory, shows that the mixing (or random walk) of the magnetic field lines yields a value of $\kappa_\perp/\kappa_\parallel$ that is of the order 0.01–0.1 (Jokipii 1966; Jokipii & Parker 1969; Mathaeus et al. 1995), much larger than the simple scattering result. Values of this general order of magnitude are in fact utilized in global simulations of cosmic-ray modulation and anomalous cosmic rays to make them agree with observations (Kóta & Jokipii 1995), and this can be used to argue that the larger value is indeed correct. Nonetheless, these inferred larger values of $\kappa_\perp/\kappa_\parallel$ have not been verified with direct observations and are not universally accepted. For example, Marshall & Stone (1978) reported non-negligible transport of MeV particles perpendicular to the 6 hr average magnetic field direction. The magnetic field directions used in their analysis, however, were not local values since the field data were measured on separate spacecraft (*HEOS 1* and *HEOS 2*) from the anisotropy data (*IMP* 7). Anath, Agrawal, & Rao (1973) and Kane (1974) reported large deviations of the (24 hr) average azimuthal anisotropy vector from the average magnetic field direction, using ground-based neutron monitor data sensitive to GeV Galactic cosmic rays (see also Forman 1975). Christon (1982) also reported significant cross-field transport of MeV particles, but again using nonlocal magnetic field and solar wind data. Zwickl & Roelof (1981), on the other hand, found that cross-field transport of protons of less than MeV energies was negligible for 1 hr averaged data. Direct observational determinations of $\kappa_\perp/\kappa_\parallel$ using local magnetic field, solar wind, and particle anisotropy data is therefore desirable.

The STEP instrument on the *Wind* spacecraft has observed several intense, energetic ion events associated with corotating interaction regions (CIRs) since its 1994 November launch. CIRs are produced by the collision of low- and high-speed solar wind streams with forward and reverse shocks usually forming between 1 and 5 AU (Gosling, Hundhausen, & Bame 1976; Burlaga 1995). Although the association of energetic particles, extending up to several MeV nucleon^{-1}, with CIRs has been known for at least two decades (see, e.g., Barnes & Simpson 1976), details about the acceleration and transport of these particles are still unclear and remain an active area of research (Richardson et al. 1993; Fisk 1996). Since even a

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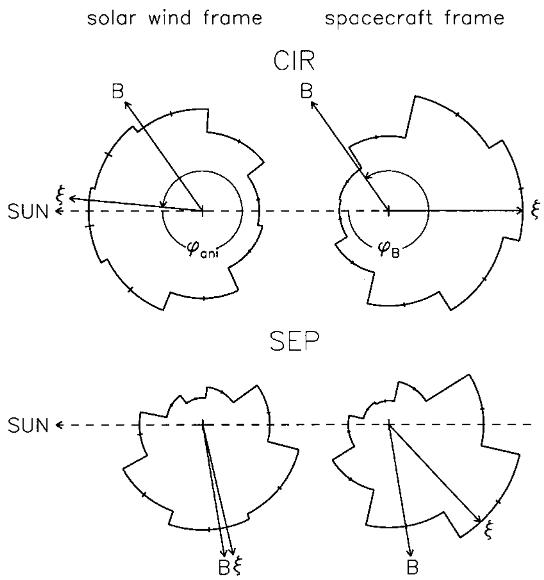

FIG. 1.—80–154 keV nucleon^{-1} helium intensity vs. azimuthal angle (of the particle velocity) for CIR particles (*top*) and for solar energetic particles (*bottom*). The right-hand plots show intensities measured in the spacecraft frame. The left-hand plots show intensities transformed into the solar wind frame. The solid vectors are the directions of the anisotropy and the local, average magnetic field as measured on the spacecraft. The CIR data are averaged over approximately a 20 minute time period centered at 1995 DOY 150.750, and the SEP data are averaged over a time period of approximately 55 minutes centered at 1995 DOY 294.921.

modest amount of cross-field transport can greatly extend the space accessible to the particles, the determination of $\kappa_\perp/\kappa_\parallel$ for CIRs is necessary for the accurate modeling of the acceleration in and around CIRs and the subsequent propagation of the energetic particles through the heliosphere. More generally, CIRs provide an excellent laboratory for studying the fundamental problem of energetic particle transport (Richardson 1985) since they often create very high particle intensities in the STEP energy range ($\lesssim$1 MeV nucleon^{-1}), lasting several days, with large anisotropies directed toward the Sun.

In this Letter we report results from the analysis of the three most intense CIRs measured on *Wind* between 1994 November and 1997 March. These CIRs have onset times measured near the Earth of approximately 1994 December 6 (day of year [DOY] 340), 1995 April 7 (DOY 97), and 1995 May 30 (DOY 150).

2. OBSERVATIONS

The STEP instrument, which consists of two large-area (0.4 cm^2 sr) time-of-flight mass spectrometers, measures He-Fe in the suprathermal energy range (von Rosenvinge et al. 1995). Because *Wind* spins once every 3 s, the STEP sensors scan the ecliptic plane, measuring the particle differential intensity in six energy bins between ~20 keV nucleon^{-1} and 1.2 MeV nucleon^{-1} in eight azimuthal sectors, with the telescope field of view sampling a region up to $\sim\pm35°$ from the ecliptic plane. Because the STEP matrix rate data were used in the analysis, and not the PHA data, the measured anisotropy directions are not subject to the bias described by Roelof (1974).

Ions triggering STEP near the low-energy threshold have speeds only about four times greater than the solar wind speed, so a Compton-Getting correction must be performed in order to transform the anisotropies measured in the spacecraft frame into the solar wind frame. In the solar wind frame, the large-scale electric field vanishes, and there is no transport across magnetic field lines because of $E \times B$ drift.

The Compton-Getting transformation, though conceptually simple, can be complicated to implement (Forman 1970). As a result, the exact transformation is often made more manageable with various simplifying assumptions (Ipavich 1974). However, because of the large effects of the transformation at these energies, we have attempted to use as few approximations as possible in this work. Specifically, we do not assume a particular spectral form, we allow the energy spectra to vary as a function of the azimuthal angle, and we use the full nonlinear transformation with respect to V_{sw}/w, where w is the particle speed and V_{sw} is the solar wind speed.

In this analysis, the solar wind velocity is measured by the Solar Wind Experiment (SWE) on board the *Wind* spacecraft (Ogilvie et al. 1995). The solar wind data measured by SWE are of sufficient accuracy (with relative errors of less than 3%) that uncertainties in the anisotropy associated with the solar wind measurements are small. The uncertainties due to the Compton-Getting transformation are usually dominated by the uncertainties in the energy spectra, which in turn are governed by counting statistics in the 42 sectored energy bins. The time intervals over which the data are averaged are chosen in order to collect adequate statistics for the analysis, and the statistical uncertainties resulting from the Compton-Getting transformation are included in the results. For example, during the highest particle intensities in the CIRs, the time intervals are ~10 minutes. The average solar wind velocity for each time period is calculated by weighting the 92 s averaged solar wind velocities with the STEP valid event rates.

Figure 1 shows azimuthal plots of the particle intensity and magnetic field direction in the *X*-*Y* geocentric solar eclipse (GSE) plane for a time period of ~20 minutes during the 1995 May 30 CIR and for a period of ~55 minutes during the 1995 October 20 (DOY 293) gradual solar flare (Reames et al. 1997). The right-hand plots are data in the spacecraft frame. The left-hand plots are data in the solar wind frame, after a Compton-Getting transformation. The magnetic field directions are measured by the Magnetic Field Investigation (MFI), also on board *Wind* (Lepping et al. 1995). The average magnetic field direction for the selected time periods are calculated from the 92 s averaged unit vectors $\boldsymbol{B}/|B|$, weighted with the STEP valid event rates. Time periods when the polar angle, θ, was greater than 60° were excluded from the analysis.

In the figure, for the CIR particles, the anisotropy direction actually changes from antisunward to sunward when transforming from the spacecraft frame to the solar wind frame—underlining the importance of an accurate Compton-Getting transformation. The sunward particle current in the solar wind frame, which indicates a source beyond 1 AU, is consistent with a CIR origin of the particles. Furthermore, unlike the solar flare anisotropy, the CIR anisotropy is not directed along the average magnetic field line, which implies substantial perpendicular transport.

For the three CIRs of this study, the *Wind* spacecraft was 66, 231, and 244 R_E upstream of the Earth for the 1994 December 6, 1995 April 7, and 1995 May 30 CIRs, respectively, and was 177 R_E upstream for the 1995 October 20 solar energetic particle (SEP) event. These large distances from the Earth's magnetosphere make it unlikely that the anisotropies measured by STEP for these events were influenced by the Earth's magnetic environment (Christon 1982). Furthermore, time periods that contain upstream ion events were excluded

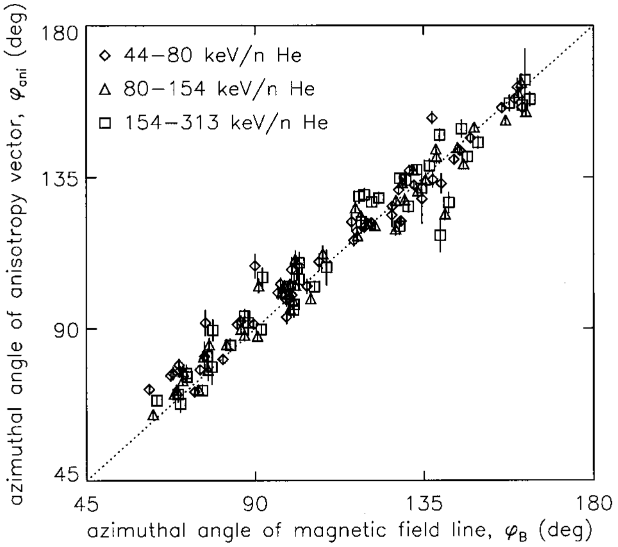

FIG. 2.—Azimuthal angle of the anisotropy vector in the solar wind frame, ϕ_{ani}, vs. the azimuthal angle of the local magnetic field line, ϕ_B. Each data point corresponds to a separate time period of ~55 minutes between 1995 DOY 294 and 296 during the rise and gradual decay phase of a large, gradual solar energetic particle event.

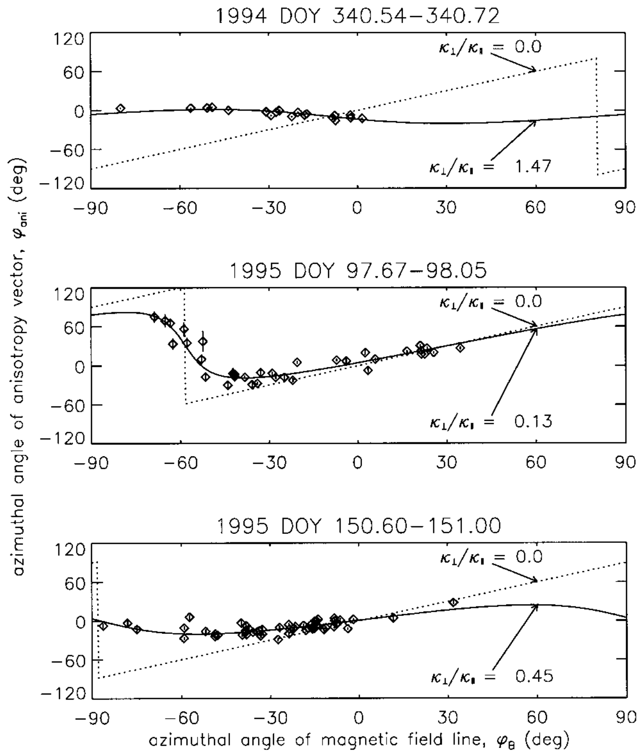

FIG. 3.—Azimuthal angle of the anisotropy vector for 80–154 keV nucleon^{-1} helium in the solar wind frame, ϕ_{ani}, vs. the azimuthal angle of the local magnetic field line, ϕ_B, during the three CIRs of this study. The solid line is the result of a least-squares fit of eq. (1) to the data, with resulting best-fit parameters of $\kappa_\perp/\kappa_\parallel = 1.47 \pm 0.07$ and $\phi_{grad} = 171°$, $\kappa_\perp/\kappa_\parallel = 0.13 \pm 0.02$ and $\phi_{grad} = 212°$, and $\kappa_\perp/\kappa_\parallel = 0.45 \pm 0.05$ and $\phi_{grad} = 182°$, respectively, for the three time periods. The dashed curves show the $\kappa_\perp/\kappa_\parallel = 0$ cases, which are excluded with high statistical significance.

from the analysis. The upstream ion events, which occur when the spacecraft is magnetically connected to the bow shock, appear as short duration (~10 minute) spikes in the low-energy particle intensity and are easily distinguished from particles of CIR or SEP event origins (Mason, Mazur, & von Rosenvinge 1996).

As a check on our particle anisotropy analysis, we have examined the transport of solar energetic particles during the 1995 October 20 gradual solar flare. At 1 AU during such SEP events, helium particles propagate typically along the magnetic field direction (Beeck et al. 1990). Figure 2 shows the ~55 minute averaged azimuthal angle of the anisotropy vector for He in the solar wind frame, ϕ_{ani}, plotted against the azimuthal angle of the local magnetic field line, ϕ_B. Note that the large range of ϕ_B also allows a test of the functional relationship between ϕ_{ani} and ϕ_B: in this case $\phi_{ani} = \phi_B$. The excellent correlation, along with the small (≲10°) scatter in the data points about the $\phi_{ani} = \phi_B$ line, shows that the solar particles propagate along the field line regardless of the orientation of the magnetic field and that residual errors such as those from fluctuations in the magnetic field and solar wind velocity are small—which gives confidence that our analysis is indeed correct.

3. DISCUSSION

The CIR anisotropy shown in Figure 1 demonstrates that the relationship $\phi_{ani} = \phi_B$, seen for the SEP anisotropies in Figure 2, does not always hold. We therefore ask how might ϕ_{ani} depend on ϕ_B in the presence of both parallel and perpendicular transport? Let us assume that the particle flux, $\boldsymbol{J}$, is linearly related to the gradient of the particle distribution function, ∇f, by the diffusion equation. While this relationship strictly applies only for near isotropy, it should be approximately valid for the moderate anisotropies discussed here. The antisymmetric part of the diffusion tensor, which corresponds to a Hall flux, can be neglected since in order for the Hall flux to contribute significantly to the observed cross-field flux (e.g., in Fig. 1), the particle density gradient must have a scale length comparable to the particle gyroradius (e.g., 10^{-4} AU for 80–154 keV nucleon^{-1} helium). Furthermore, this large gradient would have to persist over distances of approximately 0.1 AU since, as we will show below, large perpendicular transport is observed for time periods lasting over 12 hr. In this Letter, we shall also ignore the effects of the z-component of the density gradient on the x and y-components of the particle flux (in GSE coordinates) since these terms will cancel when averaging over fluctuations in the magnetic field direction.

In terms of the azimuthal angles ϕ_{ani}, ϕ_B, and ϕ_{grad} of the vectors $\boldsymbol{J}$, $\boldsymbol{B}$, and ∇f, respectively, the equation

$$\tan(\phi_{ani} - \phi_{grad}) = \sin(\phi_B - \phi_{grad})\cos(\phi_B - \phi_{grad}) \times [(\kappa_\perp/\kappa_\parallel)/(1 - \kappa_\perp/\kappa_\parallel) + \cos^2(\phi_B - \phi_{grad})]^{-1} \quad (1)$$

follows directly from the diffusion equation, where $\kappa_\perp/\kappa_\parallel$ is the ratio of the perpendicular and parallel diffusion coefficients.

If we assume that (1) $\kappa_\perp/\kappa_\parallel$ depends only weakly on ϕ_B and ϕ_{grad} and (2) on the timescale of hours, over which the magnetic field direction varies rapidly, other quantities that govern particle transport, such as the diffusion coefficients and the density gradient, are approximately constant, then equation (1) becomes a simple expression relating ϕ_{ani} and ϕ_B with the constant parameters $\kappa_\perp/\kappa_\parallel$ and ϕ_{grad}.

Figure 3 shows the ~10 minute averaged ϕ_{ani} versus ϕ_B for the three CIRs of this study. ϕ_{ani} is found from the first harmonic of a Fourier expansion that has been fitted to the particle in-

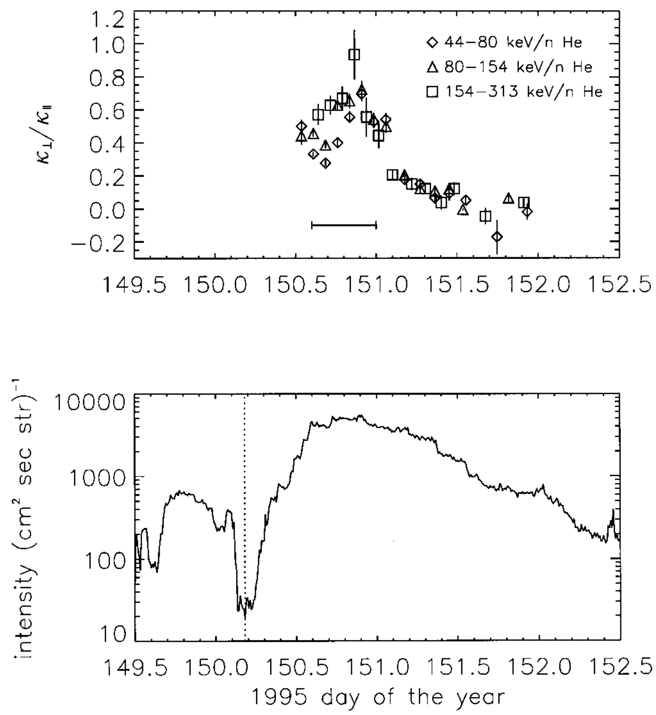

FIG. 4.—$\kappa_\perp/\kappa_\parallel$ vs. time (*top*) for the 1995 May 30 CIR for three energies. $\kappa_\perp/\kappa_\parallel$ is calculated for each time period from $\phi_{\rm ani}$ and ϕ_B by assuming that $\phi_{\rm grad} = 180°$. The bottom panel shows the 44–620 keV nucleon^{-1} helium intensity for the same time period. The dip in the helium intensity seen at DOY 150.2 coincides with the passage of the stream interface (*dashed line*). The horizontal bar shows the time period for this CIR used in Fig. 3.

tensity versus azimuthal angle data (as measured in the solar wind frame) with the method of least squares. The solid curves are the best fit of equation (1) to the data for 80–154 keV nucleon^{-1} He with the free parameters $\kappa_\perp/\kappa_\parallel$ and $\phi_{\rm grad}$. The dashed lines show the case in which $\kappa_\perp/\kappa_\parallel = 0$ and illustrate the magnitude of the disagreement between the data and purely parallel transport. The excellent agreement between the data and the functional form of equation (1) lends support to the analysis. In addition, this result is not sensitive to the time period over which the data is averaged for averaging times ranging from 92 s up to 1 hr. We have furthermore analyzed the 44–80 keV nucleon^{-1} and the 154–313 keV nucleon^{-1} helium intensities and the carbon+nitrogen+oxygen intensities and find results very similar to those shown in Figure 3.

Figure 4 shows the ratio $\kappa_\perp/\kappa_\parallel$ for three energies of helium as a function of time for the 1995 May 30 CIR. For a period of ∼12 hr during the most intense part of the CIR, the ratio climbs to values in excess of 0.40 for all three energies. The period of large $\kappa_\perp/\kappa_\parallel$ occurs after the passage of the CIR stream interface, in the compressed, decelerated, fast solar wind portion of the CIR, and $\kappa_\perp/\kappa_\parallel$ decreases to small values at later times. We note that the high-speed solar wind streams feeding into the CIRs generally have a high level of Alfvénic fluctuations or turbulence (Belcher & Davis 1971; Matthaeus & Goldstein 1982; Tsurutani et al. 1995), which may explain the substantial perpendicular transport seen during these periods but not others, such as during the 1995 October 20 SEP event.

4. SUMMARY

For the three CIRs with the highest particle intensities observed by STEP since the launch of the *Wind* spacecraft, we observe in the solar wind frame large and statistically significant transport of energetic, 44–313 keV nucleon^{-1} helium ions perpendicular to the average, local magnetic field. It may be that this large cross-field propagation in CIRs is due to the high level of Alfvénic fluctuations observed in the fast solar wind that is convected into the CIRs. During the times of peak intensity for these CIRs, the ratio $\kappa_\perp/\kappa_\parallel$ is typically seen to exceed 0.10, with values reaching as high as 1.5. These ratios, which persist for time periods measured in hours, are significantly larger than values commonly found in the literature for cross-field particle transport, suggesting that the role of perpendicular transport in the heliosphere and in many other astrophysical environments should be reexamined.

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