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The Predominance of Field-Aligned MeV Particle Flows in the Inner Heliosphere- a Survey of Anisotropy Data Covering More Than Two Solar Cycles

I. G. Richardson [1,2]

[1]*Code 661, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA*

[2]*Department of Astronomy, University of Maryland, College Park, MD 20742, USA*

Abstract

From a survey of 25 years of 15-minute-averaged ~1 MeV interplanetary ion anisotropies from the GME experiment on IMP 8, and 4 years of similar data from ISEE 3, we conclude that low-energy particle flows in the inner heliosphere near the ecliptic are predominantly closely field-aligned. Although recent WIND observations of ~100 keV/amu ions in the vicinity of CIRs suggest that there may be substantial transport of charged particles across magnetic field lines, and that the usual assumption of weak cross-field diffusion may need to be re-examined, our observations suggest that in general, cross-field diffusion is of secondary importance. We also point out features of >35 keV ions observed by the ISEE 3 spacecraft in the vicinity of CIRs which may be pertinent to the interpretation of CIR-associated ions.

1 Introduction:

Recent WIND spacecraft observations of ~100 keV/amu ions during several-hour duration periods near corotating interaction regions (CIRs) (Dwyer et al., 1997) have provided evidence for substantial transport of charged particles across magnetic field lines. In particular, the particle flow vector was not aligned with the magnetic field as would be expected if $K_{\perp}/K_{//} = 0$. The authors suggest that the observations may call for a re-examination of the role of cross-field diffusion in the heliosphere and other astrophysical environments. While other studies have suggested that there may be non-negligible perpendicular transport (e.g., Marshall and Stone, 1978), there are also studies which suggest that cross-field transport is negligible (e.g., Zwickl and Roelof, 1981). This topic is of current interest because significant perpendicular diffusion has been proposed as a means of generating the corotating low-energy particle enhancements observed by the Ulysses spacecraft at high heliolatitudes (Kóta and Jokipii, 1995). These particles are assumed to diffuse poleward following acceleration in the vicinity of CIRs, which form at low latitudes. An alternative model assumes that particles diffuse along field lines which reach high latitudes in the inner heliosphere but connect with low-latitude CIRs in the outer heliosphere (e.g., Fisk, 1996; Simnett and Roelof, 1997). In this paper, we examine ion flows in the inner heliosphere using 25 years of 15-minute ~1 MeV interplanetary ion anisotropies from the Goddard Medium Energy (GME) experiment on IMP 8, and 4 years of data from the ISEE 3 VLET instrument. We will also briefly review previous observations of low-energy (> 35 keV) ion anisotropies in CIRs observed by ISEE 3 which may be pertinent.

2 Observations:

The IMP 8 observations are 15-minute averages from the GME experiment (Richardson and Reames, 1993) covering October 1973 to November 1998. Anisotropy observations are available for: 0.5-4 MeV/amu and 4-22 MeV/amu protons and He; 1.7-12 MeV/amu $Z \geq 2$ ions; and 20-80 MeV protons. Particle counts are accumulated in eight azimuthal sectors as the spacecraft spins. IMP 8 is in a ~40 R_e geocentric orbit and spends ~60% of each orbit in the solar wind. Here, we only consider observations made in the solar wind. Particle flows may occasionally be influenced by field-line connection to the bow-shock, but we have not considered this effect in this survey. At these energies, there is negligible contamination from upstream ion events. For the IMP 8 survey, solar wind parameters have been interpolated from the 1-hour NSSDC OMNI database, which is usually based on IMP 8 observations when the spacecraft is in the

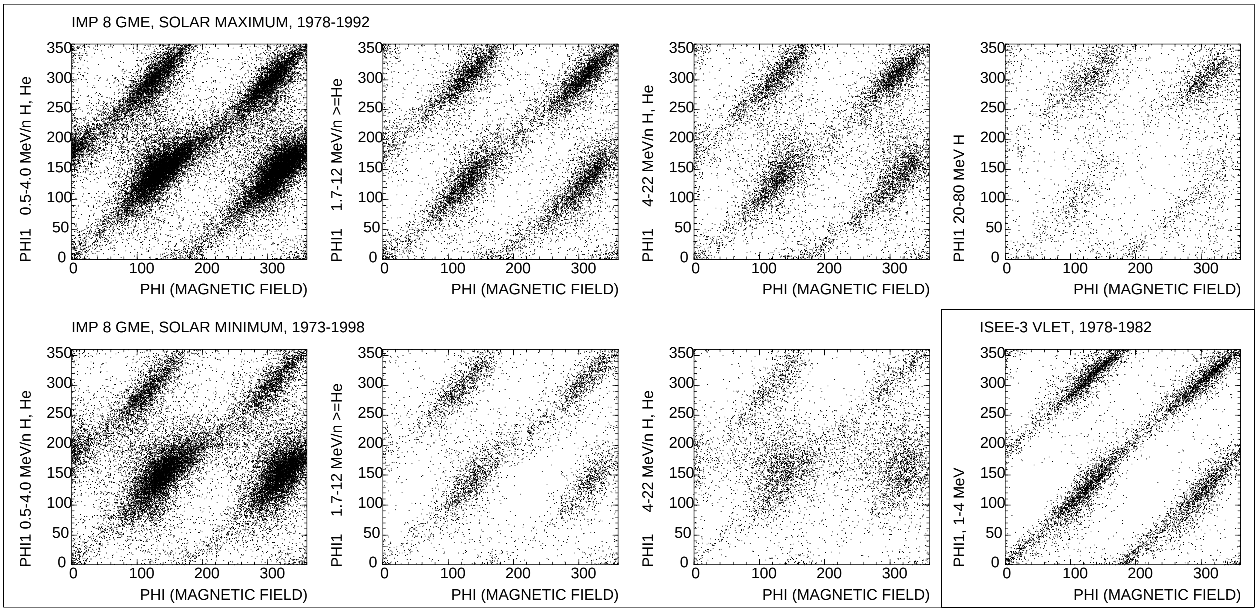

Figure 1: Plots of particle flow azimuth vs. IMF azimuth for 25 years of 15-minute averaged IMP 8 data , divided into solar maximum and solar minimum periods, and 4 years of ISEE 3 data. The predominance of field-aligned flows is evident.

solar wind. The ISEE 3 particle data used here are 15-minute averaged 1-4 MeV ion observations, again measured in eight azimuthal sectors, made during the period when the spacecraft was in orbit around the L1 libration point (August 1978-October 1982). The ISEE 3 magnetic field data are simultaneous observations from the JPL magnetometer on ISEE 3.

Figure 1 summarizes particle flow azimuths (ϕ_{an}) (0° = anti-solar flow, 90° = flow from the east, etc.) vs. solar wind magnetic field azimuth (ϕ_B, GSE coordinates) for the IMP 8 and ISEE 3 data in the solar wind frame. The Compton-Getting correction is generally small for these particles (v_p/V_{sw} >>30), so that the main conclusions of this paper are also evident in the uncorrected (spacecraft-frame) data. To remove intervals where the flow direction is poorly represented by the first-order anisotropy, we require: $\sigma\phi_{an} \leq 20°$, $A_1 \geq 0.1$, $A_1>A_2$, and $A_1>A_3$, where $\mathbf{A}_{1..3}$ are the first…third order components of a Fourier series fit to the sectored particle count rates, and ϕ_{an} is given by the direction of $\mathbf{A}_1$. The IMP 8 data are divided into "solar minimum" (1973-77, 1983-87, and 1993-1998) and other ("solar maximum") periods. The panels contain from 4360 to 39580 data points. The clear grouping of the points around $\phi_B = \phi_{an}, -\phi_{an}$ indicates that the particle flows are predominantly closely aligned with the magnetic field direction. The scatter of the sunward flows is slightly larger because these data typically are less intense, have smaller anisotropies, and hence have generally larger errors. The ISEE 3 1-4 MeV observations in the bottom right panel include an additional constraint that $\sigma\phi_B \leq 20°$. These data show particularly clear field-aligned flows.

To consider the implications of these observations in terms of $K_\perp/K_{//}$, we use the expression of Dwyer et al. (1997) relating the particle flow, particle density gradient, and magnetic field directions to $K_\perp/K_{//}$. The particle gradient direction is not measured. Thus, we first make a best estimate of $K_\perp/K_{//}$ over successive intervals of 6 hours by assuming that ϕ_{grad} is approximately constant during each interval. Figure 2 summarizes the fraction of intervals which lie in each $K_\perp/K_{//}$ bin of width 0.01 for the < 22 MeV/amu data sets in Figure 1. The results, which are similar for each data set, suggest that, most frequently, $K_\perp/K_{//}$ ~0. The median value of $K_\perp/K_{//}$ for the data in Figure 2 is ~0.05. We have also estimated $K_\perp/K_{//}$ for individual 15-minute data by making the reasonable assumption that particle gradients are predominantly radial rather than azimuthal (e.g., Zwickl and Roelof, 1981). Figure 3 shows distributions of $K_\perp/K_{//}$ obtained from the <22 MeV data sets in Figure 2 with this assumption. Negative values in Figure 3 indicate that the observations do not fit the simple diffusion model, because ϕ_{an} is not intermediate between ϕ_B and ϕ_{grad}. The sharp

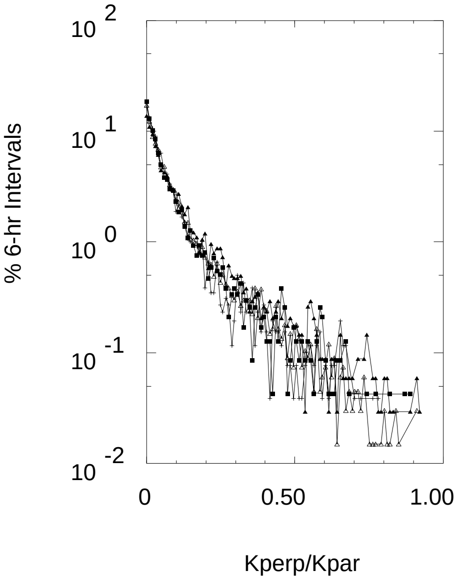

Figure 2: Summary of $K_\perp/K_{//}$ for 6-hr intervals using the < 20 MeV data in Figure 1.

peak at $K_\perp/K_{//} = 0$ indicates that propagation is most likely to be field-aligned. The median values of $K_\perp/K_{//}$ are ±0.12 to 0.26. The largest effect causing $K_\perp/K_{//} \neq 0$ appears to be errors in the flow and field directions. For example, a 10° error in ϕ_{an} would, for a Parker spiral magnetic field, produce an error in $K_\perp/K_{//}$ of ~0.18. Similar results are obtained using different ϕ_{grad}s because the flows are predominantly field-aligned and not critically influenced by ϕ_{grad}. There are intervals where the analysis suggests that $K_\perp/K_{//}$ may be large. However, examination of a limited selection of these intervals suggests that small-scale structures in the magnetic field may contribute to differences between the anisotropy and average magnetic field directions. In several IMP 8 examples, we found that the OMNI field data were not based on IMP 8 observations, emphasizing that ideally, the solar wind and particle observations should be from the same spacecraft. Thus a careful consideration of the influence of small-scale structures may be necessary before conclusions are made regarding $K_\perp/K_{//}$. Finally, were perpendicular diffusion significant, the distribution in Figure 3 would be expected to show a dominance of positive values, i.e., the data would be consistent with the diffusion-convection model. The large occurrence rate of negative values indicates instead that many of the observations do not fit the expectations of the diffusion model, again probably due to uncertainties in the flow, field and gradient directions.

3 Discussion:

We conclude that, although localized regions where $K_\perp/K_{//} >> 0$ cannot be ruled out, our extended data set demonstrates that ~1-80 MeV particle transport, at least in the inner heliosphere at ~1 AU, is predominantly field-aligned. We note that Dwyer et al. (1997) suggested that increased Alfvénic fluctuations in high-speed streams associated with CIRs might contribute to enhanced perpendicular diffusion. This is not particularly evident in our observations at solar minimum, when CIR-associated events are predominant. The observation of predominantly field-aligned streaming suggests that high latitude corotating particle events are most plausibly formed by particles streaming along field lines following acceleration in the outer heliosphere, a process which is analogous to the formation of corotating events detected at Earth.

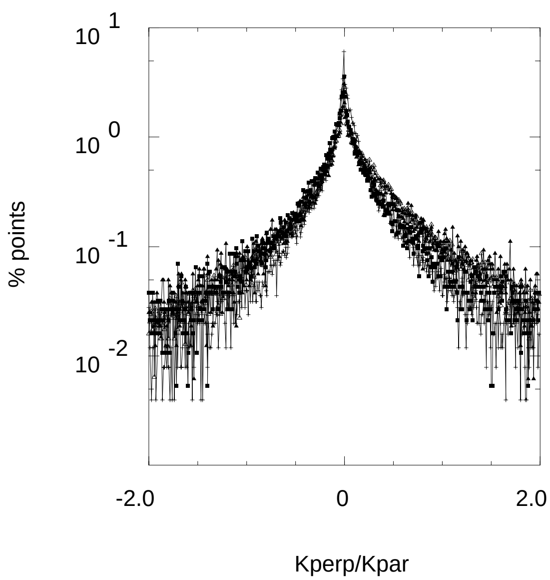

Figure 3: Summary of $K_\perp/K_{//}$ derived from 15-minute averaged data assuming a radial particle gradient.

A final point we would like to make is that Richardson and Hynds (1981), Richardson (1983), Richardson and Zwickl (1984) and Richardson (1985) noted that < 100 keV ion enhancements are a common feature of CIRs at 1 AU in the region between the stream interface and trailing edge. These enhancements, which they suggested may be stochastically accelerated from the solar wind plasma, were present in seven out of the nine CIRs in 1978-79 examined using three-dimensional 35-1600 keV ion data from the ISEE 3 EPAS instrument. These enhancements had softer spectra, extending only to ~200 keV, and different anisotropies, than those of particles streaming sunward from remote CIR shocks. These low-energy ions were streaming away from the Sun along the field lines in 5/7 cases. Figure 4 (after Richardson and Zwickl, 1984) shows a low-energy

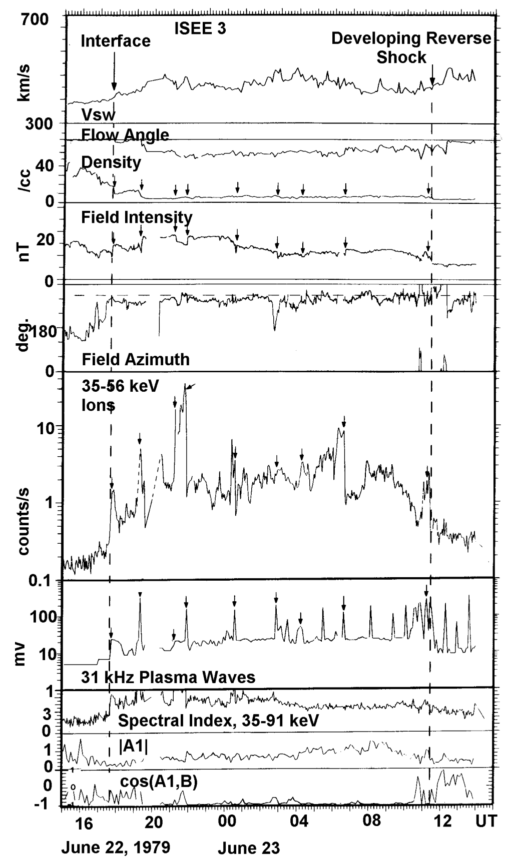

Figure 4: Example of a low energy ion enhancement inside the trailing edge of a CIR, observed by ISEE 3 on June 22-23, 1979. Note the abrupt 35-56 keV ion intensity changes at solar wind discontinuities (arrows) and the enhancement at the developing reverse shock.

ion enhancement inside the trailing edge of a CIR observed in June 1979. This is distinct from the sunward streaming enhancement in the high-speed stream extending to >1.6 MeV which was detected following the period in Figure 4 (see Figure 4 of Richardson and Zwickl (1984)). The ions show predominantly anti-solar, near field-aligned streaming (cos($\mathbf{A}_1$, $\mathbf{B}$)~ -1, with ϕ_B~300°). Several abrupt changes in the 35-56 keV ion intensities in Figure 4 are associated with local magnetic field discontinuities (arrows) and can occur within one 16-s integration time, suggesting that these particles are responding to local solar wind structures. Thus, their propagation may not necessarily be described in terms of the diffusion-convection model and large-scale particle gradients. There is also a local enhancement associated with a developing reverse shock. Here, cos($\mathbf{A}_1$, $\mathbf{B}$) suggests possible deviations from field-aligned flow, as well as a general flow reversal. We note that the April 7, 1995 event discussed by Dwyer et al. (1997) also encompassed a reverse shock, which might have influenced the particle populations present. In summary, the ISEE 3 observations suggest that ion anisotropies inside CIRs at 1 AU may be influenced by the presence of several particle populations, including locally-accelerated particles, and that these may be intimately linked to small-scale solar wind features. Thus, caution may need to be exercised in interpreting low energy ion observations in the vicinity of CIRs in terms of the simple diffusion-convection model.

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References

Dwyer, J. R., et al., Ap. J., 1997, 490, L115.
Fisk, L. A., 1996, J. Geophys. Res., 101, 15547.
Kóta, J. & Jokipii, 1995, J. R., Sci. 268, 1024.
Marshall, F. E., & Stone, E. C., 1978, Geophys. Res. Lett., 83, 3289.
Richardson, I. G., 1983, Ph.D. Thesis, University of London.
Richardson, I. G., 1985, Planet. Space Sci., 33, 557.
Richardson, I. G., and Hynds, R. J., Proc. 17th Int. Cosmic Ray Conf., 3, 430.
Richardson, I. G., & Reames, D. V., 1993, Ap. J.(Supl.), 85, 411
Richardson, I. G., & Zwickl, R. D., 1984, Planet. Space Sci., 32, 1179
Simnett, G. M., & Roelof, E. C., 1997, Adv. Space. Sci., 19(6), 859.
Zwickl, R. D., & Roelof, E. C., 1981, J. Geophys. Res., 86, 5449.