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ANGULAR DISTRIBUTIONS OF Fe/O FROM *WIND*: NEW INSIGHT INTO SOLAR ENERGETIC PARTICLE TRANSPORT

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ABSTRACT

We examine the angular distributions of He, O, and Fe in large solar energetic particle (SEP) events measured on the *Wind* spacecraft. We report, for the first time, that in a fixed velocity interval, Fe/O is often larger for particles flowing *sunward* along the magnetic field than for particles flowing outward from the Sun in many SEP events. This occurs because the anisotropy for O exceeds that for Fe, even though both species are streaming outward. There are no examples of events for which the outward Fe/O dominates. The behavior of Fe and O conflicts with the expectations of simple diffusion theory, that angular distributions should be independent of species. It also seems to conflict with the idea that energetic Fe scatters less than O of the same velocity. However, preliminary modeling suggests that the presence of a reflecting magnetic boundary beyond 1 AU, together with the increased scattering of O over Fe due to proton-generated Alfvén waves, can explain the direction and magnitude of the effect. These observations add a new dimension to the study of SEP transport.

Subject headings: acceleration of particles — shock waves — Sun: abundances — Sun: coronal mass ejections (CMEs) — Sun: particle emission

1. INTRODUCTION

Solar energetic particles (SEPs) in the large "gradual" SEP events are accelerated at shock waves driven out from the Sun by coronal mass ejections (CMEs; Kahler et al. 1984; Gosling 1993; Reames 1995, 1999, 2002; Kahler 1994, 2001; Tylka 2001). This acceleration is mediated by proton-amplified Alfvén waves produced as the particles stream away from the shocks (Bell 1978; Lee 1983, 1997). Ions of a given speed, but differing charge-to-mass ratios (Q/A), resonate with different regions of the evolving wave spectrum; hence, they scatter differently as they propagate away from the source, causing complex temporal variations in their relative abundances (e.g., Tylka, Reames, & Ng 1999; Ng, Reames, & Tylka 1999; Reames 1999; Reames, Ng, & Tylka 2000; Tylka 2001; Reames & Tylka 2002). Thus, particle abundance ratios, such as He/H or Fe/O, are powerful probes of the varying wave spectrum encountered by the particles along the magnetic field lines that connect the observer to the shock.

Particle angular distributions are a more direct means to study particle transport in the interplanetary medium. The Low-Energy Matrix Telescope (LEMT) of the Energetic Particles: Acceleration, Composition and Transport experiment (von Rosenvinge et al. 1995) on the *Wind* spacecraft has provided a unique platform for the study of angular distributions. The large geometry of LEMT (51 cm^2 sr) permits the onboard accumulation of statistically useful angular distributions of ions up through Fe that have provided new information on the SEP transport through the interplanetary plasma (Reames, Ng, & Berdichevsky 2001).

For particle scattering against a Kolmogorov spectrum of Alfvén waves, quasi-linear theory predicts the pitch-angle diffusion coefficient $D_{\mu\mu} \sim vP^{-1/3}$, where v is the velocity and P is the magnetic rigidity, or momentum per unit charge, of the SEP ions. This implies that the scattering mean free path $\lambda \sim v/D_{\mu\mu} \sim P^{1/3}$. The difference in rigidity of Fe and O at the same velocity is a factor of ≈2, so $D_{\mu\mu}$ for Fe would be about 26% smaller than that for O. Because of this difference in pitch-angle scattering, Fe tends to arrive earlier than O in many events, producing abundance ratios Fe/O that are large initially and decrease with time (Reames et al. 2000).

In this Letter, we examine the angular distributions of Fe and O, and we report, for the first time, variations of Fe/O with the direction of particle flow along the magnetic field in large SEP events. This allows us to combine the information deduced from particle abundance variations with that deduced from angular distributions to study more fully the transport of SEP ions in the inner heliosphere.

2. ANGULAR DISTRIBUTIONS OF He, O, AND Fe

Dominant ion species are identified by the LEMT on board *Wind* at high rates and are binned by energy and species. The angular distributions discussed in this Letter were accumulated in 16 sectors relative to the azimuth of the magnetic field. The process of identifying and binning ions by LEMT has been discussed in detail by Reames et al. (2001). In order to improve the statistics for the rare species such as Fe, we have summed the sectored data into two hemispheres that distinguish ions moving outward and sunward along the magnetic field. Note that Reames et al. (2001) considered smaller angular intervals.

Let us begin by considering a single species in two different energy intervals. Figure 1 shows He intensity *versus* time at 2.5–5 and 5–8 MeV amu^{-1} for the outward and sunward hemispheres in the 1998 May 2 event. The interval with the highest energy (and rigidity) has the smallest outward-to-sunward intensity ratio. Therefore, the energy spectrum is *harder* for ions flowing *sunward* than for those flowing outward. All of the other events reported in this Letter show similar systematic behavior.

Although the He anisotropy in this event is clearly too large for spatial diffusion theory to apply, ostensibly one may still understand the velocity (or energy) dependence *qualitatively* using the classical diffusion model with impulsive injection from a point source. For $\lambda \sim r^{\alpha}$, the model predicts the anisotropy $\xi = 3r/[(2 - \alpha)vt]$, where r is the radial distance and t is the time. The v-dependence implies that the He anisotropy

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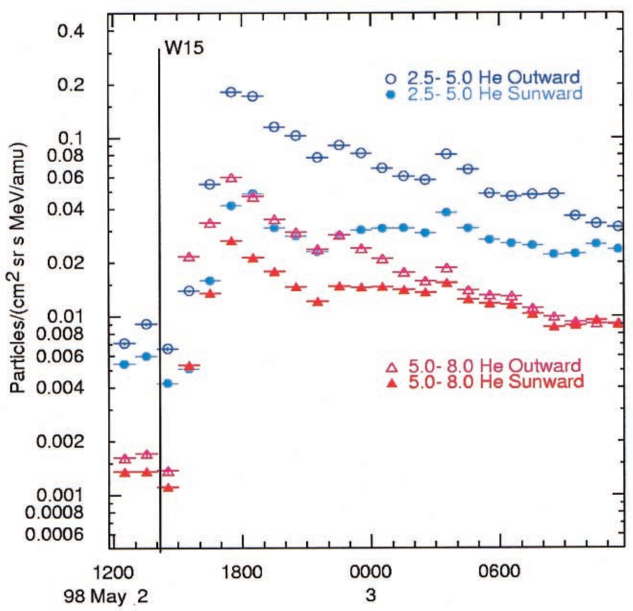

FIG. 1.—Intensities shown for He of 2.5–5 MeV amu^{-1} (*blue circles*) and 5–8 MeV amu^{-1} (*red triangles*) in the outward (*open symbols*) and sunward (*filled symbols*) hemispheres along the magnetic field.

will decay faster in the higher energy channel, consistent with the observation. However, if α is independent of species, the simple diffusion model also predicts that ξ is independent of λ and particle species and, presumably, that there is no difference in the angular distribution of two different species like Fe and O with the same v but different λ. In contrast, weak-scattering models would predict Fe to be more anisotropic than O early in the event.

Figure 2 shows the intensities of Fe and O at 2.5–5 MeV amu^{-1} and Fe/O *versus* time for the outward and sunward hemispheres, together with plasma parameters, for three SEP events. Notice that, some hours into the event, Fe/O is systematically larger in the sunward direction than in the outward direction. This occurs because *the outward-to-sunward ratio in intensities* (*i.e., the anisotropy*) *is larger for* O *than for* Fe. *These observations conflict with the predictions of both the diffusion model and the weak-scattering theory* discussed above. Of course, the outward intensities exceed or equal the corresponding sunward intensities in all cases. SEPs from the events of 1998 May 2 and May 6 propagate inside large magnetic clouds from prior CMEs where the ion streaming is quite large, as can be seen from the directional intensities (see also Reames et al. 2001). The event of 2000 April has higher intensities, reduced streaming, and a stronger decrease of Fe/O with time, yet it also shows a reduced but systematic enhance-

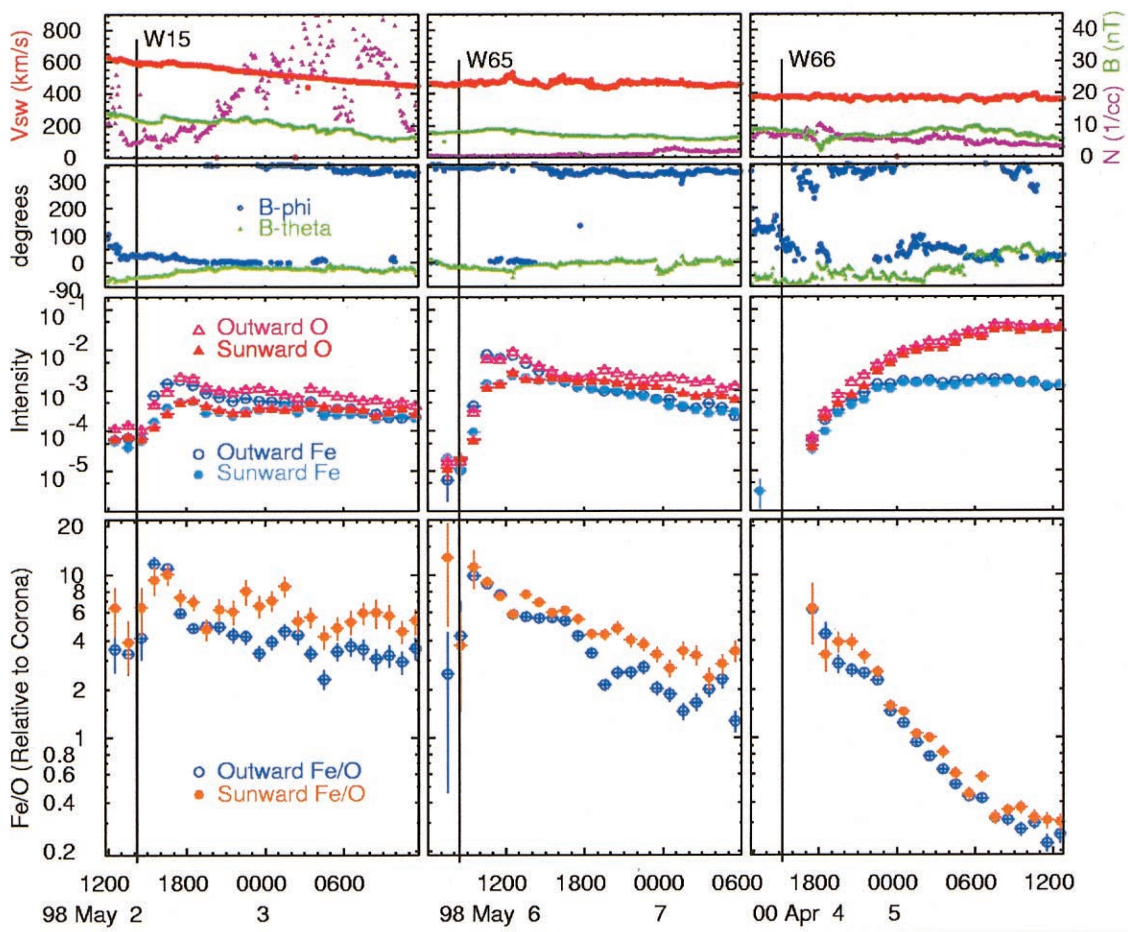

FIG. 2.—Energetic particle and solar wind plasma parameters shown as a function of time for the SEP events of 1998 May 2, 1998 May 6, and 2000 April 4. For each event, the upper panel shows the solar wind speed (*red points*) and density (*violet points*) and the magnetic field strength (*green points*), and the second panel shows the magnetic field direction. The third set of panels show the intensities [particles/(cm^2 sr s MeV amu^{-1})] of 2.5–5 MeV amu^{-1} O (*red triangles*) and Fe (*blue circles*) in the outward- (*open symbols*) and sunward-flowing (*filled symbols*) hemispheres along the magnetic field. The lower panels show Fe/O, relative to the coronal ratio (0.134), in the outward- (*open blue circles*) and sunward-flowing (*filled orange circles*) hemispheres relative to the magnetic field.

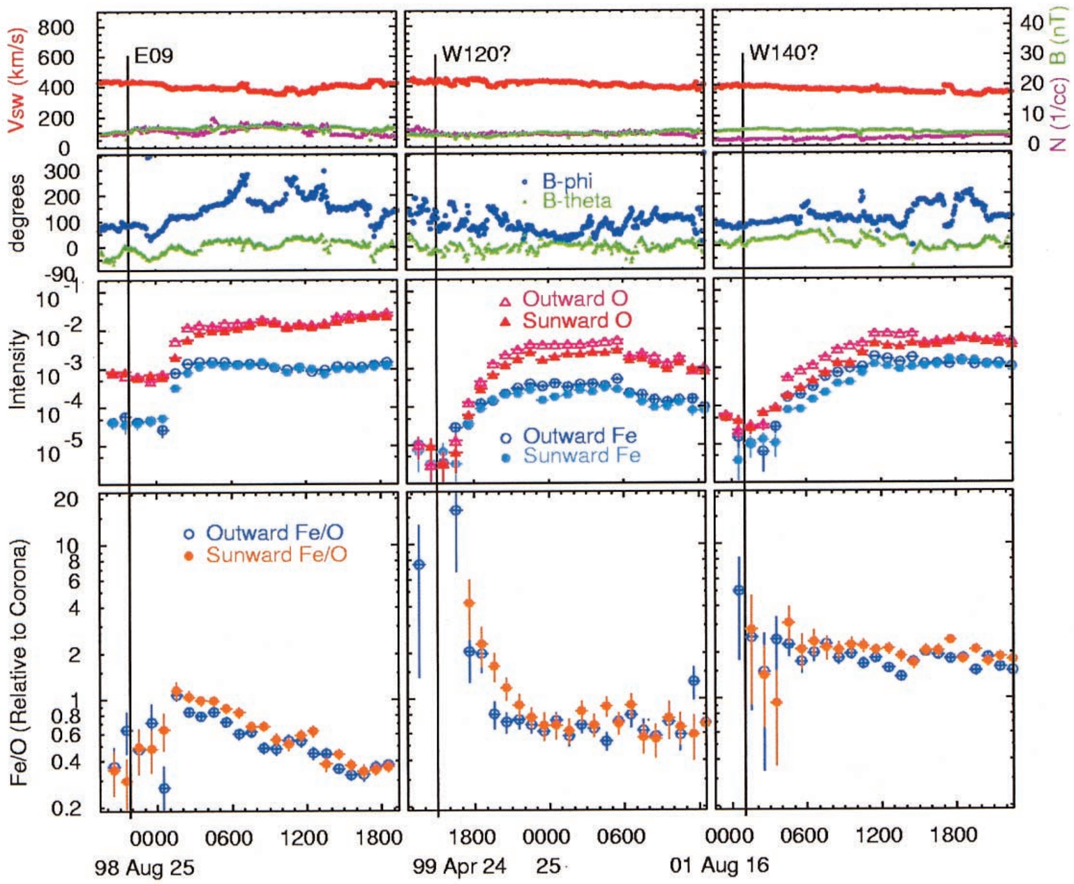

FIG. 3.—Energetic particle and solar wind plasma parameters (as described in Fig. 2) shown as a function of time for the SEP events of 1998 August 24, 1999 April 24, and 2001 August 16.

ment in the sunward Fe/O. All three of these events involve source CMEs from magnetically well-connected western solar longitudes. However, the enhanced sunward Fe/O does not occur especially early in these events; rather it tends to occur near or after the peak intensities of Fe.

Figure 3 shows data similar to that in Figure 2, but for three events with sources at very different longitudes. The event of 1998 August 24 comes from E09, while the events of 1999 April 24 and 2001 August 16 are back-side events. In fact, the event of 2001 August 16 shows a back-side halo CME that may come from quite far beyond the west limb of the Sun. Yet, these events all show small but significant enhancements in the sunward Fe/O.

We summarize the behavior of Fe/O for these six events in Table 1 where we have summed the data for a 12 hr period beginning ∼4 hr after the event onset. In other events, the enhancement in the sunward Fe/O is smaller, or Fe/O is statistically isotropic. However, we find no SEP events for which the *outward* Fe/O dominates.

TABLE 1

DIRECTIONAL Fe/O RATIOS AVERAGED OVER 12 hr PERIODS

Event Date	Outward Fe/O	Sunward Fe/O
1998 May 2	4.00 ± 0.12	6.10 ± 0.27
1998 May 6	4.43 ± 0.077	5.38 ± 0.12
1998 Aug 24	0.654 ± 0.015	0.753 ± 0.019
1999 Apr 24	0.665 ± 0.027	0.813 ± 0.041
2000 Apr 4	0.888 ± 0.019	1.04 ± 0.025
2001 Aug 16	1.76 ± 0.041	2.02 ± 0.060

We should note that the angular distributions of He/H measured by LEMT show the same direction and magnitude as those of Fe/O (see Reames et al. 2001). However, small differences in the energy/nucleon intervals for H and He make it more difficult to exclude velocity dependences in the He/H observations. We *can* compare He and O in the same velocity interval. Here we find that the anisotropies of the two species are similar, so that O/He is more nearly isotropic, since He and O have comparable values of Q/A.

3. DISCUSSION AND CONCLUSIONS

We have shown events for which the Fe/O for ions flowing sunward along the magnetic field is as much as ∼50% larger than that for outward-flowing ions. This is equivalent to an outward-to-sunward ratio of O intensity that is ∼50% larger than that of Fe. As mentioned above, simple diffusion theory would predict no difference in the anisotropies of Fe and O, despite differences in the scattering mean free path, so that Fe/O would be independent of direction. Note that for the diffusion model, extended injection from a spherical shell would result in larger anisotropy for Fe than for O, contrary to observations, and the effect is also far smaller than observed. Furthermore, although in principle this symmetry can be broken by the addition of convection with the solar wind velocity V_{sw}, estimates of this $O(V_{sw}/v)^2$ effect suggest that it can produce differences of only a few percent late in the event. The large anisotropies in the events of 1998 May 2 and 6 (Fig. 2), with the largest asymmetry in Fe/O, suggest that we should explore models that support the weak-scattering limit. However, the model of Ng et al. (1999), which follows the pitch angle and spatial transport of ions in the presence of magnetic focusing and self-generated waves, is unable to explain the observations because it uses a free-escape outer boundary.

We were able to simulate the correct direction and magnitude of the sunward Fe/O enhancement only when we began to consider a recent transport model with a partially reflecting outer boundary at ~1.8 AU (C. K. Ng & D. V. Reames 2002, in preparation). This aspect of the model was developed to accommodate the transport of particles injected inside the magnetic cloud of a preexisting CME by a new shock-accelerated source near the Sun, a common occurrence in SEP events. Because of its weaker pitch-angle scattering, Fe reaches the boundary much earlier than O. There, Fe is reflected and returns to produce a flatter spatial gradient with reduced anisotropy. However, the relatively early onset of the enhanced sunward Fe/O requires a boundary that is not too far beyond 1 AU. The average rate of 2.5 CMEs day^{-1} near solar maximum (Webb & Howard 1994) corresponds to about 1 AU spacing between CMEs within each steradian around the Sun. While only a small fraction of CMEs are fast enough to accelerate SEPs, all contribute to a complex magnetic topology that lends itself to the production of "reflecting boundaries." On 1998 May 2, a CME passed Earth ~10 hr (~0.14 AU) prior to the event onset.

Note that in the limit of scatter-free transport, the presence of a reflecting boundary will not produce the observed effect. In this limit, Fe and O will be reflected at the boundary simultaneously, and the model produces the same spatial and angular distribution for Fe and O. Increased interplanetary scattering of O over Fe in conjunction with the "reflecting" boundary is necessary to produce the effect. Preliminary modeling suggests that wave growth enhances the magnitude of the sunward enhancement in Fe/O. Even in events with moderate proton intensities, such as those in 1998 May, the model produces the correct magnitude of the sunward enhancement in Fe/O.

For some events, such as the 2000 April 4 event shown in Figure 2, preferential trapping of O near the shock may cause the Fe/O ratio escaping from the shock to decrease with time as Fe leaks away, so that newer material flowing outward has an intrinsically lower Fe/O ratio than the older backscattered material. This would also cause O to peak later than Fe, as observed.

We have reported a systematic enhancement in Fe/O for sunward-flowing ions that is a frequent occurrence in large SEP events. This enhancement occurs because of a larger anisotropy for O than for Fe. Preliminary modeling suggests that a reflecting boundary beyond 1 AU, as well as preferential scattering of O by proton-generated waves, is required to explain the observations. These observations provide a significant new perspective on the transport of energetic ions in the inner heliosphere.

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