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TRANSVERSE FLOW DEFLECTIONS ASSOCIATED WITH FAST CORONAL MASS EJECTA IN INTERPLANETARY SPACE

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ABSTRACT

Using a bidirectional electron heat flux signature to identify coronal mass ejections, CMEs, in the solar wind at 1 AU, we find that the fast CMEs which drive interplanetary shocks are preferentially deflected eastward in transit outward from the sun. A corresponding westward deflection usually occurs in the compressed ambient solar wind plasma ahead of these CMEs. We suggest that this preferential pattern of deflections is caused primarily by the asymmetrical draping of the ambient interplanetary magnetic field about fast CMEs.

INTRODUCTION

Transverse flow deflections are commonly observed near the leading edges of quasi-stationary, corotating high speed solar wind streams at 1 AU [e.g., Siscoe *et al.*, 1969; Gosling *et al.*, 1972]. The sense of these deflections, first westward and then eastward, ultimately is a consequence of solar rotation [e.g., Razdan *et al.*, 1965; Pizzo, 1978], and the shift from westward to eastward flow normally is centered on a high pressure ridge which is aligned nearly along an Archimedean spiral.

Our primary purpose here is to demonstrate that systematic west-east flow deflections are also commonly observed in transient shock wave disturbances driven by fast coronal mass ejections (CMEs). However, in contrast to the case for corotating streams, the flow reversal in transient disturbances does not coincide with a local pressure maximum. We believe it is likely that the preferential west-east flow deflection pattern observed in shock events is a consequence of solar rotation and the asymmetrical draping of the interplanetary magnetic field, IMF, about fast CMEs. A more complete description of this work can be found elsewhere [Gosling *et al.*, 1987b].

OBSERVATIONS

We have previously published evidence that a bidirectional electron heat flux is one of the more prominent signatures of a CME in the solar wind at 1 AU [Gosling *et al.*, 1987a], and in this paper we assume that such events identify CMEs. An example of a bidirectional heat flux event is shown in Figure 1. Usually, as from ~ 0700 to ~ 2000 UT on November 24, the heat flux is unidirectional, being directed outward from the sun along the IMF. Occasionally, however, as from ~ 2000 UT on November 24 until ~ 0915 UT on November 25, a bidirectional electron heat flux event with counterstreaming, field-aligned electron beams is observed.

Our previous work shows that bidirectional electron heat flux events such as shown in Fig. 1 are detected near the Earth ~ 3 times/month during periods of high solar activity. About half of all bidirectional events follow within 24 hours the passage of interplanetary shocks, but irrespective of any shock association bidirectionality usually signals spacecraft entry into a distinct entity with plasma and field characteristics different from that of the surrounding solar wind. The bidirectional heat flux normally is interpreted as evidence that the magnetic field within a CME is either connected at both ends to the sun in a bottle-like configuration, or else the field is entirely disconnected from the sun forming a closed plasmoid [e.g., Montgomery *et al.*, 1974; Bame *et al.*, 1981]. Consistent with the latter interpretation, many (but certainly not all) bidirectional events are associated with the field rotations and field intensities characteristic of "magnetic clouds."

Figure 2 displays 5-min averages of the solar wind speed (V), proton density (N), proton temperature (TP), total (ion and electron, plus field) static pressure (P), and ecliptic bulk flow angle corrected for aberration (Φ) surrounding an interplanetary shock wave disturbance. The CME (ejection) was identified by its bidirectional heat flux signature. Of particular interest to the present paper are the changes in flow angle associated with this disturbance. Within the compressed plasma behind the shock, but ahead of the CME, the flow was deflected primarily westward ($+\Phi$), while within the CME driving the shock the flow was deflected primarily eastward ($-\Phi$). The flow reversal occurred nearly simultaneous with entry into the CME. Note that, in contrast to the case for corotating events, the flow reversal did not coincide with a local pressure maximum. Rather, the pressure peaked at the shock and declined relatively smoothly thereafter.

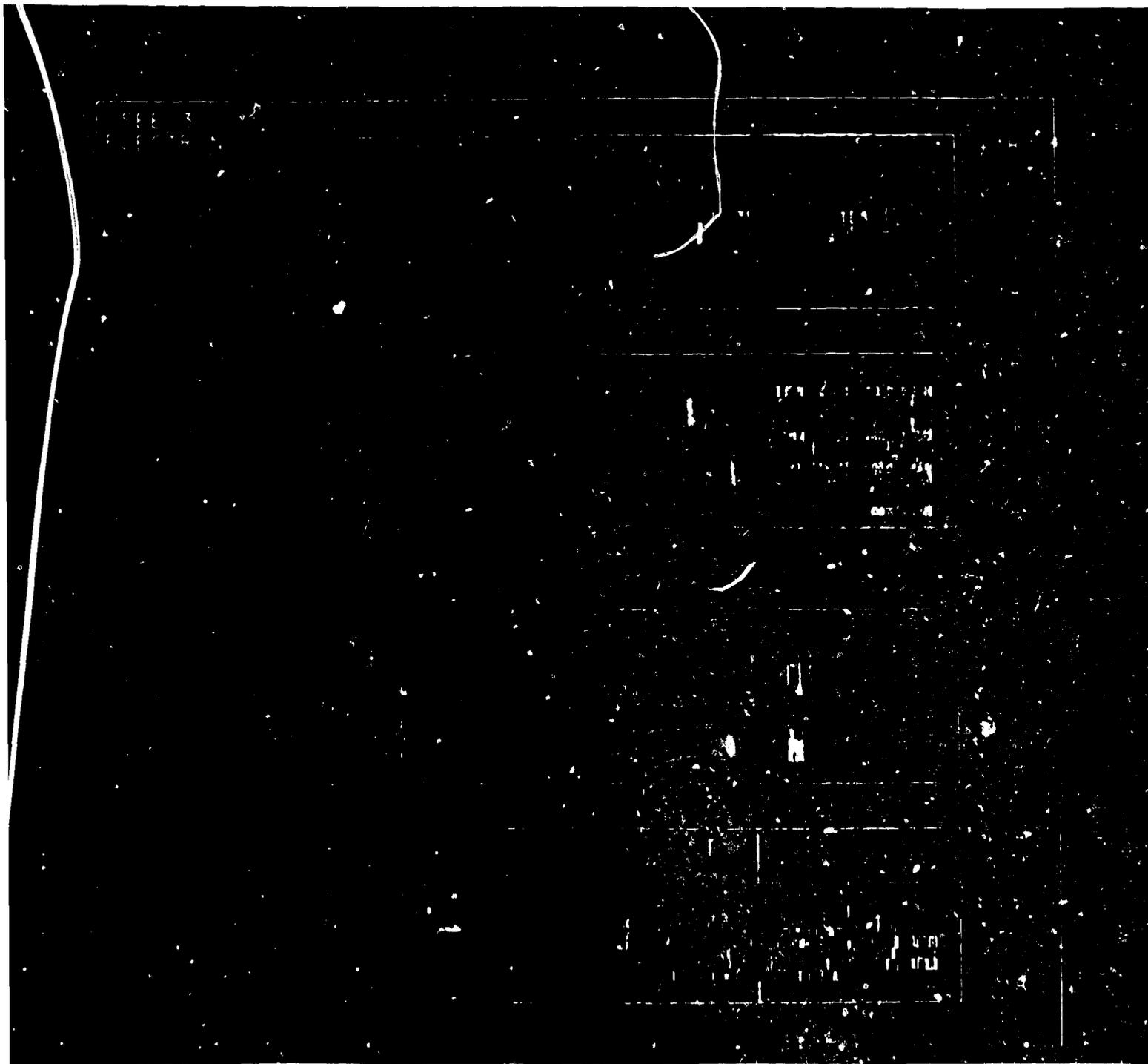


Fig. 1. A color-coded representation of ISEE 3 measured solar wind electron angular distributions within an energy passband extending from 137 to 363 eV on November 24-25, 1978. As indicated by the vertical bar on the left, color coding of the angular distributions is related to the log of the measured counts within $\pm 67.5^\circ$ of the spacecraft equatorial plane. Numbers at the right hand edge of the panels refer to the azimuthal look angle of the measurement, 0° corresponding to the solar direction. The energy passband shown is dominated by the halo population which carries the electron heat flux. Note the onset of an intense bidirectional heat flux event shortly after ~ 2000 UT on November 24 and persisting until about 0910 UT on November 25. This event was not shock associated. From Gosling *et al.* [1987a].

Using our ISEE 3 measurements we have identified 19 shock events in the August 1978–December 1979 interval where the spacecraft also encountered the CME (that is, a bidirectional event) driving the shock. In 17 of these 19 events west-east flow deflections such as described above were observed, while in the other 2 events the opposite deflection pattern was detected. In each case the flow reversal occurred near, but not necessarily at, the leading edge of the CME; however, as for the event shown in Figure 2, the pressure maximized near the shock rather than at the position of the flow reversal.

In order to demonstrate these characteristic azimuthal flow deflections, we have performed a superposed epoch analysis for the 17 shock events where the west-east pattern was observed, keying (zero epoch) upon the onset of electron heat flux bidirectionality. Figure 3 shows the results of this analysis. On the average, the flow within the compressed ambient plasma ahead of the CMEs was deflected $\sim 3^\circ$ to the west, while the plasma within the CMEs was deflected $\sim 3^\circ$ to the east. These flow deflections correspond to changes in the transverse ecliptic flow speed of ± 25 km/s. On the average, the flow reversal occurred several hours prior to entry into the CMEs.

Figure 4 compares a normalized histogram of all observed flow azimuths within the 19 bidirectional electron heat flux events (that is, CMEs) which were preceded by shocks with a similar histogram of observed flow azimuths for all of the data within the 16.5-month interval of this study. Even though the former histogram includes the 2 events where the opposite deflection pattern was observed, the histogram is shifted toward negative azimuths (eastward flow) by $\sim 2^\circ$.

Figure 5 provides a similar comparison of flow azimuths for a set of 24 bidirectional events which did not have high enough speeds relative to the ambient plasma to produce shocks. No average eastward or westward deflection is apparent for these events. Indeed, not only is the histogram for these relatively slow CMEs centered nearly the same as is the histogram for all the data, but it is also narrower and more strongly peaked. This result indicates that the flow deflections associated with shock events are a consequence of the dynamical interaction between fast CMEs and the slower-moving ambient solar wind.

DISCUSSION

In the absence of effects associated with solar rotation, symmetry arguments would demand that both west-east and east-west deflection patterns be equally probable in transient shock events. It is possible that the observed excess of events (17 out of 19) where the deflection pattern was west-east is a chance occurrence.

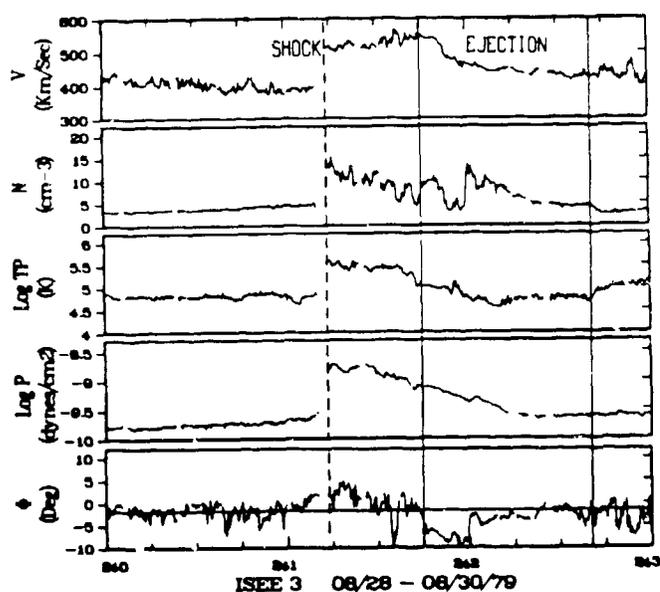


Fig. 2. Five-minute averages of selected solar wind parameters measured by ISEE-3 on August 28–30, 1979 (days of year 240–242). An interplanetary shock is indicated by the vertical dashed line, and the shock driver (bidirectional electron heat flux event) is delimited by the pair of solid vertical lines. Note the westward ($+\Phi$) deflection of the compressed plasma ahead of the driver and the eastward ($-\Phi$) deflection of the driver plasma. From Gosling *et al.* [1987b].

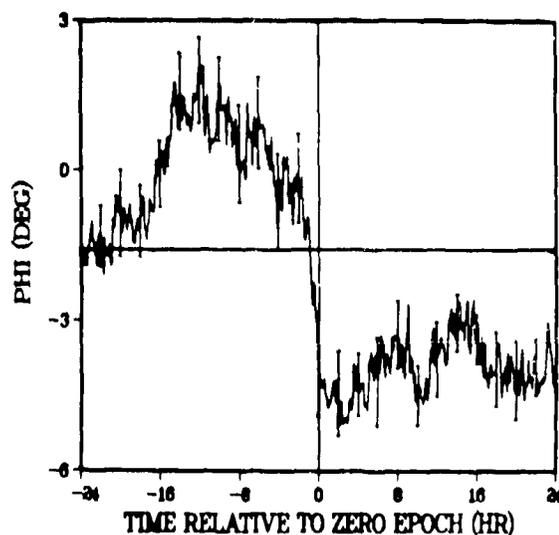


Fig. 3. Superposed epoch plot of the solar wind ecliptic flow azimuth (PHI) for 17 interplanetary shocks followed by bidirectional electron heat flux events. Zero epoch corresponds to the onset of electron bidirectionality, and the original data set consists of 5-min averaged values. PHI is positive to the west. The long-term average value of PHI, corrected for aberration, is $\sim -1.5^\circ$. Adapted from Gosling *et al.* [1987b].

However, the probability of 17 or more out of 19 events having the same deflection pattern by chance is quite low ($< 8 \times 10^{-4}$), and we believe the preponderance of west-east events represents a real physical effect.

We suggest that the preferred west-east deflection pattern can be understood as a consequence of solar rotation. As illustrated in the sketch in Figure 6, when a fast CME forces its way outward through the ambient solar wind, the ambient IMF must drape about the CME [e.g., Hundhausen, 1972; Gosling and McComas, 1987]. Such draping is a consequence of: 1) the high electrical conductivity of the interplanetary medium which "freezes" the field into the plasma and effectively prevents any substantial interpenetration of the CME by the ambient solar wind, and 2) the relative motion between the CME and the ambient solar wind. Because of the spiral nature of the ambient IMF (caused by solar rotation), the IMF drapes asymmetrically about the CME in the solar equatorial plane (we have assumed for the purposes of illustration that the CME is centered there). Field lines originally to the east of the fast CME gradually slip off the CME as it progresses outward from the sun, while field lines to the west increasingly drape about it. Thus the magnetic pressure should be higher on the westward edge of a fast CME than on the eastward edge. The restoring forces associated with magnetic field tension are also directed eastward across the CME. The combined effect of the magnetic pressure and tension therefore is to deflect the CME eastward. As illustrated in Figure 7, these forces may, in addition, reorient (as well as deform) the CME leading to an asymmetrical disturbance front.

In addition to field effects, azimuthal inhomogeneities in the ambient solar wind might contribute to the preferential eastward deflection of fast CMEs. Solar rotation causes quasi-stationary inhomogeneities in the solar wind to be bent into spirals. The net effect of this curvature is that low speed inhomogeneities tend to curve into the path of a fast CME from the west, leading to stronger CME/ambient plasma interactions on the west side of a fast CME than on the east side.

Whatever the cause of the preferential eastward deflection of fast CMEs, the paired nature of the deflections observed (first westward within the compressed ambient plasma and then eastward within the CME) must be a consequence of the conservation of transverse momentum. That is, any transverse momentum gained by the CME must be lost by the ambient plasma, and vice versa.

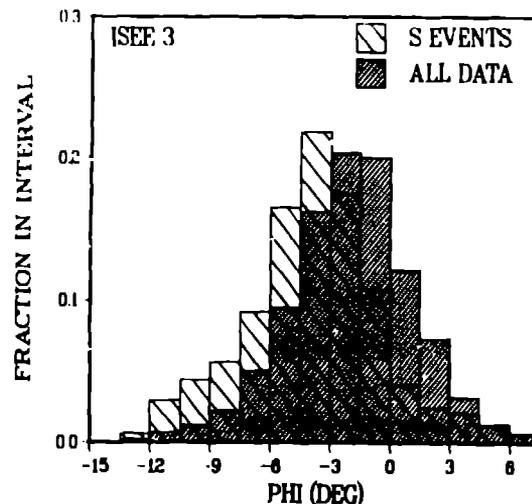


Fig. 4. Histograms of the relative frequency of occurrence of the flow azimuth angle (PHI) within 19 bidirectional electron heat flux events preceded by interplanetary shocks (S events) as compared to the entire 16.5-month data set of this study (all data). PHI is positive for flows directed to the west. Adapted from Gosling *et al.* [1987b].

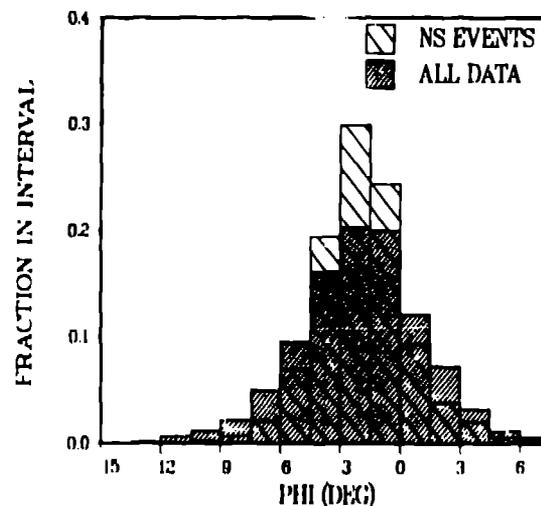


Fig. 5. Similar to Figure 4 for 24 bidirectional electron heat flux events which were not shock-associated (NS events). Adapted from Gosling *et al.* [1987b].

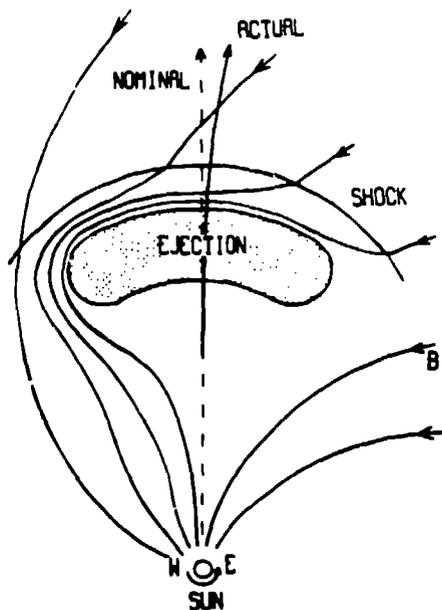


Fig. 6. A sketch illustrating how the ambient spiral interplanetary magnetic field drapes about a fast coronal mass ejection, here drawn as a detached plasmoid in the solar equatorial plane. The magnetic stresses associated with draping provide a force which deflects the ejection eastward. Adapted from Gosling et al. [1987b].

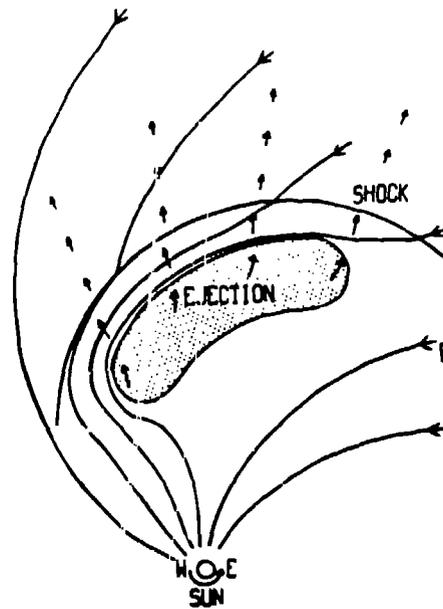


Fig. 7. A sketch illustrating the possible shock disturbance/coronal mass ejection geometry in the solar equatorial plane resulting from the magnetic stresses associated with draping. The small arrows are flow vectors. From Gosling et al. [1987b].

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REFERENCES

- Bame, S. J., J. R. Asbridge, W. C. Feldman, J. T. Gosling, and R. D. Zwickl, Bi-directional streaming of solar wind electrons > 80 eV; ISEE evidence for a closed field structure within the driver gas of an interplanetary shock, *Geophys. Res. Lett.*, **8**, 173, 1981.
- Gosling, J. T., and D. J. McComas, Field line draping about fast coronal mass ejections: A source of strong out-of-the-ecliptic interplanetary fields, *Geophys. Res. Lett.*, **14**, 355, 1987.
- Gosling, J. T., A. J. Hundhausen, V. Pizzo, and J. R. Asbridge, Compressions and rarefactions in the solar wind: Vela 3, *J. Geophys. Res.*, **77**, 5442, 1972.
- Gosling, J. T., D. N. Baker, S. J. Bame, W. C. Feldman, R. D. Zwickl, and E. J. Smith, Bidirectional solar wind electron heat flux events, *J. Geophys. Res.*, **92**, 8519, 1987a.
- Gosling, J. T., M. F. Thomsen, S. J. Bame, and R. D. Zwickl, The eastward deflection of fast coronal mass ejections in interplanetary space, *J. Geophys. Res.*, in press, 1987b.
- Hundhausen, A. J., Interplanetary shock waves and the structure of solar wind disturbances, in *Solar Wind*, NASA Spec. Rep. SP-308, edited by C. P. Sonnett, P. J. Coleman, and J. M. Wilcox, pp. 393-417, 1972.
- Montgomery, M. D., J. R. Asbridge, S. J. Bame, and W. C. Feldman, Solar wind electron temperature depressions following some interplanetary shock waves: Evidence for magnetic merging?, *J. Geophys. Res.*, **79**, 3103, 1974.
- Pizzo, V., A three-dimensional model of corotating streams in the solar wind. I. Theoretical foundations, *J. Geophys. Res.*, **83**, 5563, 1978.
- Razdan, H., D. S. Colburn, and C. P. Sonnett, Recurrent Si^{IV} - Si^{IV} impulse pairs and shock structure in M-region beams, *Planet. Space Sci.*, **13**, 1111, 1965.
- Siscoe, G. L., B. Goldstein, and A. J. Lazarus, An east-west asymmetry in the solar wind velocity, *J. Geophys. Res.*, **74**, 1759, 1969.