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Interaction of Fast Steady Flow With Slow Transient Flow: A New Cause of Shock Pair and Interplanetary B_z Event

XUEPU ZHAO

Center for Space Science and Astrophysics, Stanford University, Stanford, California

The occurrence of the nonspiral magnetic field, high helium density, "cold magnetic enhancement" and counterstreaming suprathermal electron flux in the slow flow around a forward shock indicates that the slow flow is the interplanetary counterpart of the coronal mass ejection (ICME). The characteristics of the field and plasma in the fast flow around the reverse shock are typical for a fast steady flow. Thus the shock pair here appears to be caused by interaction of a fast steady flow with a slow ICME. The fact that the slow ICME possesses a planar magnetic structure and a large $-B_z$ component suggests that the slow ICME may be disconnected from the Sun. It is shown that compression alone appears to be adequate to explain the large southward interplanetary magnetic field component within the shocked slow plasma because of the large southward field component present in the ICME ahead of the forward shock. In addition, a new method to infer the shock angle and Mach number from the observed upstream plasma β and the jump ratios of proton density and total magnetic flux density across a shock is suggested.

1. INTRODUCTION

Among the ten $-B_z$ events triggering major geomagnetic storms between August 1978 and December 1979, eight events were associated with forward shocks and occurred within the shock sheath or the gas driving the shock ahead [*Tsurutani et al.*, 1988]. The driver gas has been suggested to be the interplanetary counterpart of fast coronal mass ejections (fast ICME) [e.g., *Hoeksema and Zhao*, 1992], consistent with the well-known fact that major magnetic storms near solar maximum are caused by solar transient events. The origin of the other two events is rather difficult to understand. One is associated with no shock; the other is a shocked $-B_z$ event associated with a shock pair but shows no evidence of the presence of a fast ICME [*Tsurutani et al.*, 1988].

Two classes of shock pairs have been discussed in the literature. One is the corotating interaction region caused by fast steady flow–slow steady flow (SS) interaction. The other interaction region is caused by fast transient flow–slow steady flow (TS) interaction. Theory and observations show that both occur rarely at 1 AU [e.g., *Gosling et al.*, 1988].

The shock pair studied here has a "boxcar" shape: a forward shock (at 1140 UT, day 329, 1978) and a reverse shock (at 0140 UT, day 330, 1978) bounding the intense fields with a discontinuity (at 1714 UT) which separates the shocked fast plasma from the shocked slow plasma [see *Tsurutani et al.*, 1988, Figure 6]. This shape is typical for the corotating interaction region (CIR); thus it might be a CIR. However, ISEE 3 observations show absence of the corotating streams 27 days before and after the event [*Couzens and King*, 1986], even though the predicted source surface polarity structures look stable [*Hoeksema and Scherrer*, 1986] and previous and following appearances of shocks are observed [*Tsurutani et al.*, 1988]. Because the occurrence frequency of TS shock pairs at 1 AU appears to be greater than that of SS shock pairs [*Gosling et al.*, 1988], it is also possible that the observed shock pair is a TS shock pair with ICME centered far away from the Sun-Earth line [*Tsurutani et al.*, 1988]. For either SS or TS shock pairs the ambient plasma is the slow steady flow, and the magnetic field should be the Parker spiral. However, existence of large southward interplanetary magnetic field (IMF) components ahead of the forward shock near the solstitial month of December is hard to reconcile with a spiral field [*Russell and McPherron*, 1973]. The purpose of the present paper is to search for the causes of the observed shock pair and the $-B_z$ event by first examining physical properties of the slow flow ahead of the forward shock, in the next section, then analyzing the magnetic configuration in fast and slow flow in section 3, and predicting the jump ratio of the total magnetic flux across a fast shock and comparing it with observations in section 4. We conclude in section 5 that the shock pair and the associated $-B_z$ event are caused by the interaction of fast steady flow with slow transient flow, instead of the interaction of fast steady flow with slow steady flow or fast transient flow with slow steady flow.

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2. PLASMA PROPERTIES OF THE SLOW FLOW

Let us now examine the characteristics of the observed plasma and magnetic field around the $-B_z$ event studied here. Figure 1 displays the plasma properties and magnetic field components between November 24 and 27, 1978. The vertical dashed, solid, and dotted lines in each panel locate the forward shock, the flow interface, and the reverse shock, respectively. The $-B_z$ event studied here occurred in the shock sheath between the forward shock and the flow interface, as shown in the shaded part of Figure 1*g*.

The profiles of proton velocity, density, and temperature in Figures 1*a*, 1*b*, and 1*c* show that in addition to a velocity increase, a substantial proton temperature increase and an abrupt proton density decrease occurred at the flow interface, which is similar to the stream interface [*Burlaga*, 1974; *Gosling et al.*, 1978]. However, the profiles of proton temperature, total magnetic flux, and proton velocity (see Figures 1*c*, 1*d*, and 1*a*, respectively) indicate that the slow flow ahead of the forward shock is, instead of a slow steady flow, just a "cold magnetic enhancement" [*Burlaga et al.*, 1978],

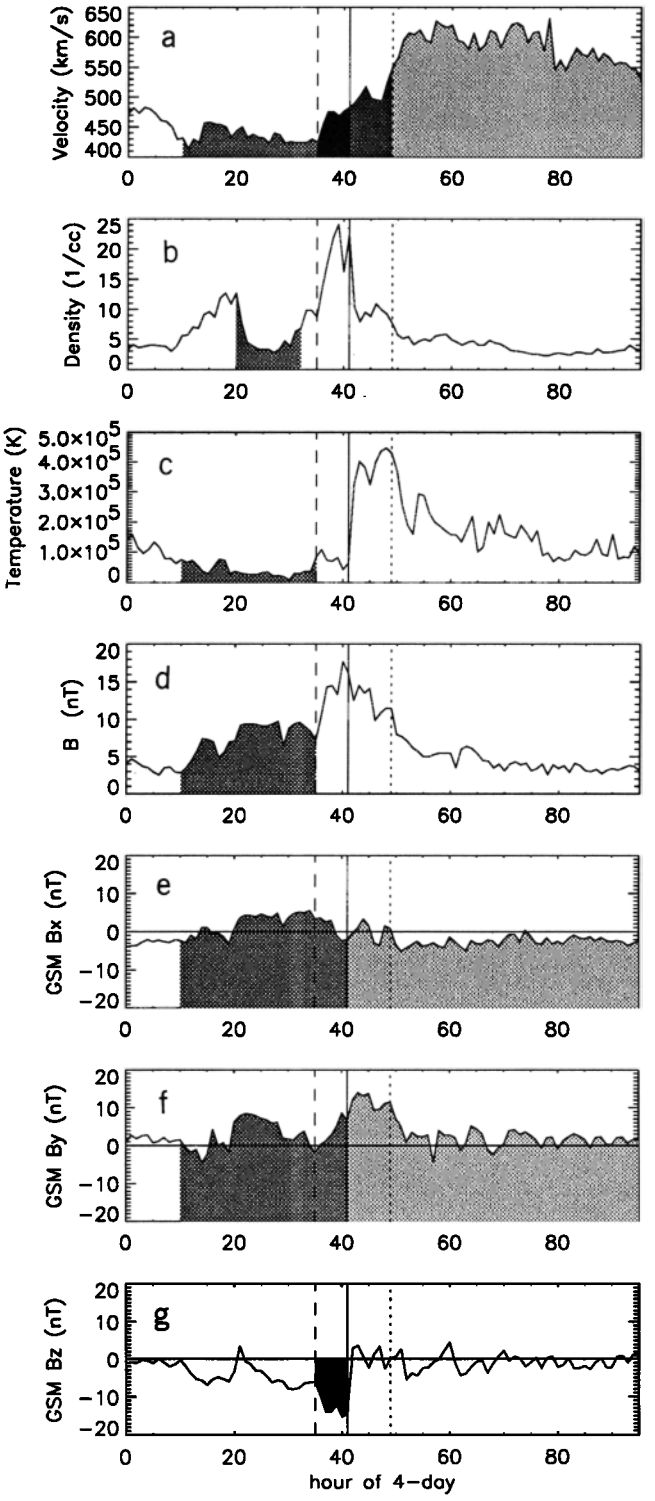

Fig. 1. Profiles of magnetic field and plasma properties between November 24 and November 27, 1978. (*a*) Flow velocity, (*b*) proton density, (*c*) proton temperature, (*d*) magnetic flux density, and (*e*) *X*, (*f*) *Y*, and (*g*) *Z* components of the magnetic field in the geocentric solar magnetospheric coordinate system. The dashed, solid, and dotted lines correspond to the forward shock, discontinuity, and reverse shock, respectively.

which is shown by the shading in Figures 1*c*, 1*d*, and 1*a*. The temperature remaining low even in the shocked plasma between the forward shock and the interface suggests that the cold magnetic enhancement probably extends to the interface. The high helium density in the shocked plasma (see the top panel of Figure 6 of *Tsurutani et al.* [1988]) also suggests that the slow flow is an ICME.

Gosling et al. [1987] found that counterstreaming flux events of suprathermal electrons (BDE) may be one of the most prominent signatures of ICME. In fact, as shown by the shading in Figure 1*b*, a BDE was observed between November 24, 2000 UT, and November 25, 0910 UT, 1978 [*Gosling et al.*, 1987], though the time interval is a bit narrower than that of the cold magnetic enhancement. *Crooker et al.* [1990] recently analyzed ICME geometry and found that the radial boundaries of an ICME were determined on the basis of low temperature, with BDE and counterstreaming proton events [*Marsden et al.*, 1987] occurring within those boundaries. Thus all plasma properties of this slow flow indicate that it is a slow ICME or slow transient flow, instead of a slow steady flow.

3. Magnetic Configuration in Fast and Slow Flow

The interplanetary magnetic field configuration on long time scales can be divided into spiral and nonspiral fields. The spiral field is formed by streams with the field angle dependent upon the plasma speed, and its expected angular distribution should cluster tightly near $(\phi, \theta) = (-45°, 0°)$ or $(135°, 0°)$ if the MHD fluctuations are weak; the distribution will be broader if the fluctuations are strong, as in the fast steady flow. Here ϕ and θ denote azimuthal (spiral) and latitudinal angles of IMF in the solar ecliptic coordinate system. The azimuthal angle of $-45°$ ($135°$) denotes field polarity away from (toward) the Sun. A nonspiral field configuration indicates fields in transient flow, e.g., the interplanetary counterparts of coronal mass ejections (ICMEs). Both rotational and nonrotational fields in ICMEs [*Gosling*, 1990] should show significant departures from the Parker spiral [*Klein and Burlaga*, 1982; *Nakagawa et al.*, 1989; *Farrugia et al.*, 1990].

We use hourly averaged values of the azimuthal and latitudinal angle of the IMF in the solar ecliptic coordinate system from November 24 to November 26, 1978, to determine the angular distributions shown in Figure 2. The time intervals for the five panels from top to bottom in Figure 2 correspond to the five intervals from left to right in Figure 1*a*. The panels in Figure 2 show the field direction for different parts of the structure: ambient, before the shock, after the forward shock before and then after the discontinuity, and after the reverse shock. The angular distribution of the field right behind the reverse shock (see Figure 2*e*) is near $(-40°, 0°)$ with rather wide diffusion, as is expected for the fast steady flow with strong fluctuations. The angular distribution for the field ahead of the forward shock shows multiple components (see Figures 2*a* and 2*b*). Figure 2*a* shows spiral field with polarity away from the Sun, the same as that behind the reverse shock, but with weak fluctuations. The structure between the spiral field and the forward shock (Figure 2*b*) is definitely not a spiral field, shown by significant departures from the direction $(-45°, 0°)$ or $(135°, 0°)$, implying that it is the field in a transient flow. Figures 2*c* and 2*d* display the angular distributions for fields within the interaction region separated by the discontinuity. The differing distributions between the two panels indicate that the discontinuity is a flow interface.

Therefore both the plasma properties and the magnetic field in the flow examined here show that the discontinuity within the shock pair is a flow interface, and the slow flow ahead of the interface is a transient flow with nonspiral field. The existence of a flow interface suggests that the shock pair is not a TS shock pair with ICME centered far away from the Sun-Earth line. The shock pair is thus caused by fast steady flow–slow transient flow interaction (ST shock pair).

4. CONTRIBUTION OF FAST SHOCK TO $-B_z$ EVENT

By averaging on the time scale of the shocked ICME, it can be estimated that the southward IMF component, total magnetic flux, and proton density jumped to 13 nT, 17 nT, and 14 protons/cm^3 from 7 nT, 10 nT, and 8 protons/cm^3, respectively, and the jump ratios across the shock are about 1.85, 1.70, and 1.75, respectively.

Generally speaking, to calculate the jump of the southward component across a fast shock, the shock normal and speed must be specified so that the upstream parameters can be inferred from observations, and downstream parameters can be predicted by the MHD jump conditions. However, it is difficult, if not impossible, to accurately determine the shock normal with only one spacecraft.

For cases when the plasma β ahead of the fast forward shock is specified to be, for example, 0.5, 1.0, and 5.0 [*Whang*, 1987; *Zhao et al.*, 1991], we calculate the jump ratios of proton density and total magnetic flux across shocks when the shock angle (the angle between the shock normal and the upstream magnetic field) increases from 0° to 90° and the Mach number increases from 1.1 to 6.0. Figure 3 shows the dependence of the total magnetic flux ratio on the proton density ratio for $\beta = 0.5$, 1.0, and 5.0. It is seen that for shock angles greater than 80° the total magnetic flux ratio approximately equals the proton density ratio no matter what the values of the Mach number and plasma β are. If the proton density ratio is less than or equal to 1.8, the magnetic flux ratio is nearly proportional to the proton density ratio when the shock angle is greater than 50°. This inference holds approximately true for β values between 0.5 and 5.0. The shock normal seems nearly parallel to the ecliptic because the gas driving the shock is a fast steady flow, and the shock angle is likely to be 50° because the latitudinal angle of field is about 50° ahead of the forward shock (see Figure 2). On the basis of Figure 3 the total magnetic flux ratio can be inferred to be close to or slightly less than the proton density ratio. The consistency between the prediction and observations shows that shock compression alone appears to be adequate to explain the large value of southward field component observed within the shocked ICME plasma.

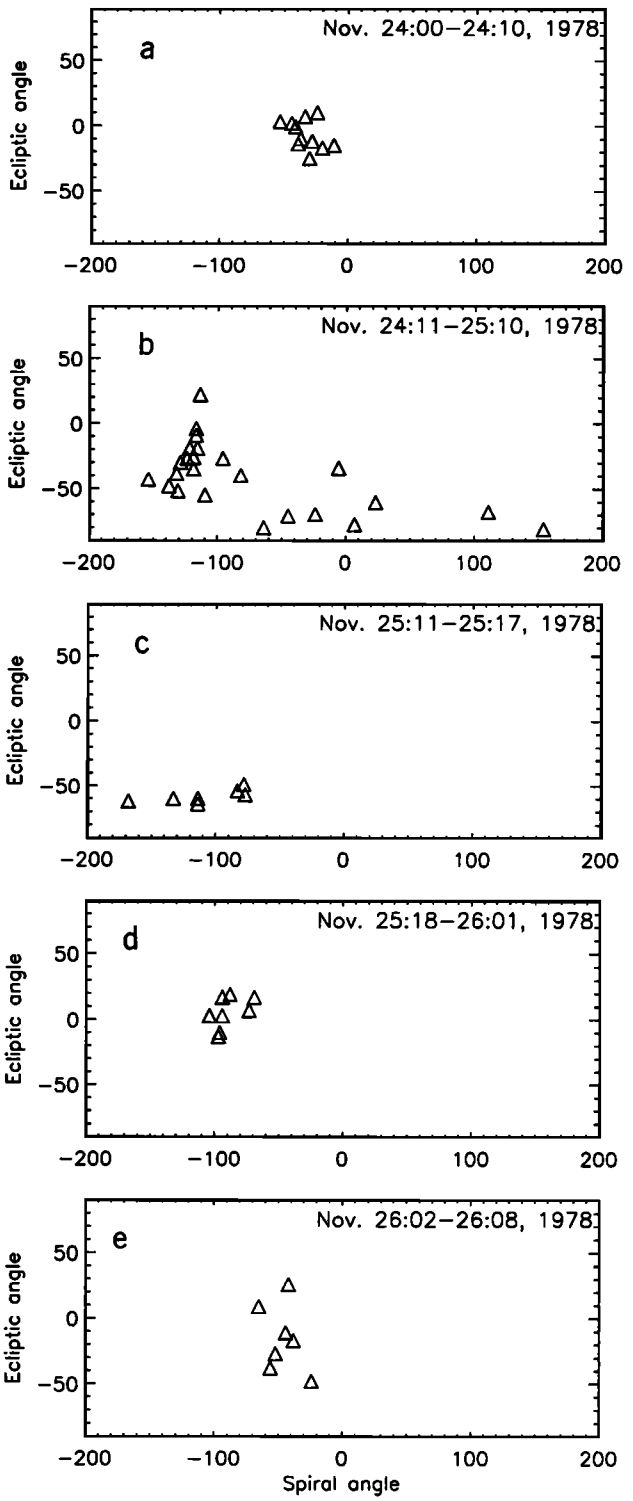

Fig. 2. Angular distributions of various plasma flows in the solar wind. (See the five intervals in Figure 1*a*.) The field direction for (*a*) ambient (0–10), (*b*) before the shock (11–34), after the forward shock, (*c*) before (35–41) and (*d*) after (42–49) the discontinuity, and (*e*) after the reverse shock (50–56).

5. CONCLUSIONS AND DISCUSSION

By examining plasma properties in the slow flow, analyzing the angular distribution of magnetic field in fast and slow flow, and estimating jump ratios of proton density and total magnetic flux, we come to the following conclusions:

1. The discontinuity between the shock pair is a flow interface. Its existence suggests that the shock pair is not a TS shock pair associated with an ICME centered far away from the Sun-Earth line.
2. The slow flow ahead of the interface is an ICME.
3. The shock pair associated with the November 25, 1981, $-B_z$ event is caused by fast steady flow–slow ICME interaction.
4. The compression alone appears to be adequate to explain the large value of $-B_z$ observed within the shocked

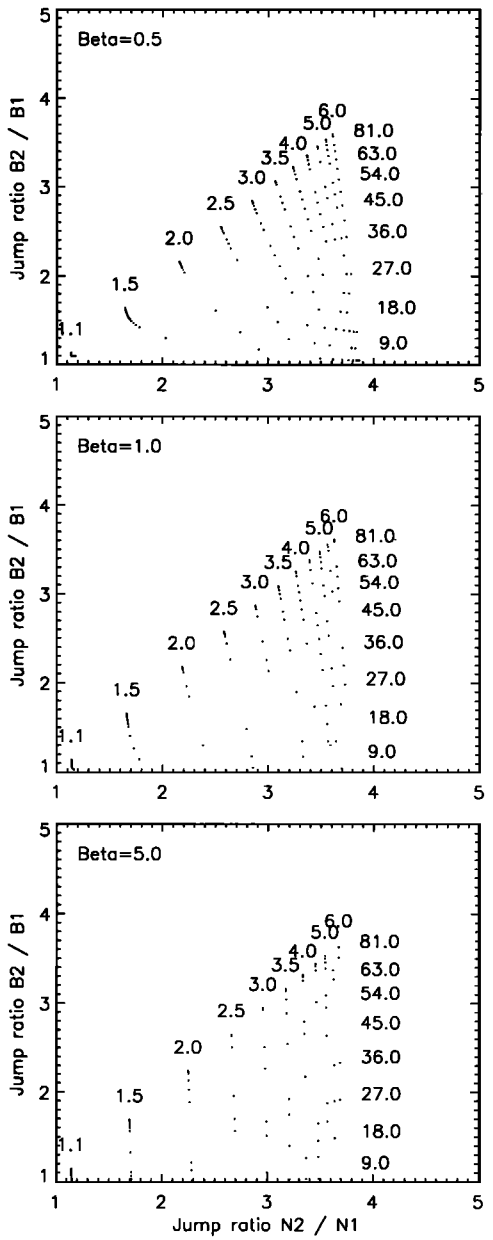

Fig. 3. Dependence of the jump ratio of magnetic flux density on the jump ratio of proton density. The plasma beta number from top to bottom is 0.5, 1.0, and 5.0, respectively. The shock angle ranges from 4.5° to 85.5°, and the Mach number ranges from 1.1 to 6.0.

ICME because of the strong upstream field which is the internal field of the ICME.

5. The interface between fast steady flow and slow ICME is similar to that between fast steady flow and slow steady flow, i.e., a velocity increase, a substantial proton temperature increase, and an abrupt proton density decrease across the interface. However, there may be a potentially large difference in that there may not be much azimuthal slippage in the ST interaction under study here. This may be the reason why the ST shock pair formed at 1 AU closer to the Sun than the SS shock pair.

6. BDE plasma is usually distinct with low proton temperature and strong, smoothly varying magnetic field. This signature indicates that coronal mass ejection events (CMEs) at 1 AU typically are closed field structures either rooted at both ends in the Sun or entirely disconnected from it [*Gosling*, 1990]. Because there is no large internal field rotation in the slow flow studied here, the flow is basically a planar structure. If the planar structure is parallel to the ecliptic plane (the XY plane of the solar ecliptic coordinate system), the shock pair is similar to the CIR, and the structure may be rooted at both ends in the Sun. However, in this case we will infer that there should be no significant north-south field component observed in the slow ICME, which is not consistent with observations. The other extreme case is that the planar structure is parallel to the meridian plane (XZ plane). In this case, a large north-south field component can be expected, and the existence of a fast steady flow–slow transient flow interaction region suggests that the ICME may be disconnected from the Sun. Therefore if the magnetic structure in the slow flow is planar, the existence of the fast steady flow–slow ICME interaction region (shock pair) with large B_z component suggests the existence of a detached ICME from the Sun.

Numerical simulations and in situ observations show [*Hundhausen and Gosling*, 1976; *Smith and Wolfe*, 1976; *Hundhausen*, 1985; *Gosling et al.*, 1988] that for fast steady flow–slow steady flow interaction, SS reverse shocks occur at heliocentric distances beyond about 1.5 AU but less than the distance of 2.5 AU where SS forward shocks start to occur. On the other hand, for fast ICME–slow steady flow interaction, the observed TS forward shocks formed within 0.3 AU, and TS reverse shocks formed beyond 1 AU. Further study of the shock pair formation is needed for the case of fast steady flow–slow transient flow interaction.

It may be interesting to note that Figure 3 provides a new way to estimate Mach number and shock angle if the upstream plasma β, the cross-shock proton density ratio, and the cross-shock total magnetic flux ratio across a shock can be specified by observations. For instance, by using the ratio values specified above we can grossly infer from Figure 3 that for the forward shock studied here the Mach number is between 1.5 and 1.6 and the shock angle is about 70°. More accurate values may be estimated if the observational values can be specified more accurately.

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REFERENCES

Burlaga, L. F., Interplanetary stream interfaces, *J. Geophys. Res.*, *79*, 3717–3725, 1974.

Burlaga, L. F., N. F. Ness, F. Mariani, B. Bavassano, U. Villante, H. Rosenbauer, R. Schwenn, and J. Harvey, Magnetic fields and flows between 1 and 0.3 AU during the primary mission of Helios 1, *J. Geophys. Res.*, *83*, 5167–5174, 1978.

Couzens, D. A., and J. H. King, Interplanetary medium data book, supplement 3, *Rep. NSSDS/WDC-A-R&S86-04*, NASA Goddard Space Flight Cent., Greenbelt, Md., 1986.

Crooker, N. U., J. T. Gosling, E. J. Smith, and C. T. Russell, A

bubblelike coronal mass ejection flux rope in the solar wind, in *Physics of Magnetic Flux Ropes, Geophys. Monogr. Ser.*, vol. 58, edited by C. T. Russell, E. R. Priest, and L. C. Lee, pp. 365–372, AGU, Washington, D. C., 1990.

Farrugia, C. J., M. W. Dunlop, F. Geurts, A. Balogh, D. J. Southwood, D. A. Bryant, M. Neugebauer, and A. Etemadi, An interplanetary planar magnetic structure oriented at a large (~80 deg) angle to the Parker spiral, *Geophys. Res. Lett.*, *17*, 1025–1028, 1990.

Gosling, J. T., Coronal mass ejections and magnetic flux ropes in interplanetary space, in *Physics of Magnetic Flux Ropes, Geophys. Monogr. Ser.*, edited by C. T. Russell, E. R. Priest, and L. C. Lee, pp. 343–364, AGU, Washington, D. C., 1990.

Gosling, J. T., J. R. Asbridge, S. J. Bame, and W. C. Feldman, Solar wind stream interfaces, *J. Geophys. Res.*, *83*, 1401–1412, 1978.

Gosling, J. T., D. N. Baker, S. J. Bame, W. C. Feldman, and R. D. Zwickl, Bidirectional solar wind electron heat flux events, *J. Geophys. Res.*, *92*, 8519–8535, 1987.

Gosling, J. T., S. J. Bame, E. J. Smith, and M. E. Burton, Forward-reverse shock pairs associated with transient disturbances in the solar wind at 1 AU, *J. Geophys. Res.*, *93*, 8741–8748, 1988.

Hoeksema, J. T., and P. H. Scherrer, The solar magnetic field—1976 through 1985, *Rep. UAG-94*, Natl. Geophys. Data Cent., Boulder, Colo., 1986.

Hoeksema, J. T., and X. Zhao, Prediction of magnetic orientation in driver gas–associated $-B_z$ events, *J. Geophys. Res.*, *97*, 3151–3157, 1992.

Hundhausen, A. J., Some macroscopic properties of shock waves in the heliosphere, in *Collisionless Shocks in the Heliosphere: A Tutorial Review, Geophys. Monogr. Ser.*, vol. 34, edited by R. G. Stone and B. T. Tsurutani, pp. 37–58, AGU, Washington, D. C., 1985.

Hundhausen, A. J., and J. T. Gosling, Solar wind structure at large heliocentric distances: An interpretation of Pioneer 10 observations, *J. Geophys. Res.*, *81*, 1436–1440, 1976.

Klein, L. W., and L. F. Burlaga, Interplanetary magnetic clouds at 1 AU, *J. Geophys. Res.*, *87*, 613–624, 1982.

Marsden, R. G., T. R. Sanderson, C. Tranquille, K.-P. Wenzel, and E. J. Smith, ISEE 3 observations of low-energy proton bidirectional events and their relation to isolated interplanetary magnetic structures, *J. Geophys. Res.*, *92*, 11,009–11,019, 1987.

Nakagawa, T., A. Nishida, and T. Saito, Planar magnetic structures in the solar wind, *J. Geophys. Res.*, *94*, 11,761–11,775, 1989.

Russell, C. T., and R. L. McPherron, Semiannual variation of geomagnetic activity, *J. Geophys. Res.*, *78*, 92–108, 1973.

Smith, E. J., and J. H. Wolfe, Observations of interaction regions and corotating shocks between one and five AU: Pioneers 10 and 11, *Geophys. Res. Lett.*, *3*, 137–140, 1976.

Tsurutani, B. T., W. D. Gonzalez, F. Tang, S.-I. Akasofu, and E. J. Smith, Origin of interplanetary southward magnetic field responsible for major magnetic storms near solar maximum (1978–1979), *J. Geophys. Res.*, *93*, 8519–8531, 1988.

Whang, Y. C., Slow shocks and their transition to fast shocks in the inner solar wind, *J. Geophys. Res.*, *92*, 4349–4356, 1987.

Zhao, X., K. W. Ogilvie, and Y. C. Whang, Modeling the effects of fast shocks on solar wind minor ions, *J. Geophys. Res.*, *96*, 5437–5445, 1991.

X. Zhao, Center for Space Science and Astrophysics, Stanford University, Stanford, CA 94305.

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