# INTERACTION OF FAST STEADY FLOW WITH SLOW TRANSIENT FLOW: A NEW CAUSE OF INTERPLANETARY $B_z$ EVENTS

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## *Abstract*

The occurrence of the nonspiral magnetic field, high helium density, Cold Magnetic Enhancement and counterstreaming suprathermal electron flux in the slow flow around the forward shock indicates that the slow flow is a CME in interplanetary space (ICME). The characteristics of the field and plasma in the fast flow around the reverse shock is typical for a high speed stream. Thus the shock pair here appears to be caused by the interaction of a high speed stream with a slow ICME. The fact that a −Bz event occurred in such a shock pair suggests that the slow ICME is disconnected from the Sun.

It is shown that compression alone appears to be adequate to explain the large southward IMF component within the shocked 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 $\beta$ and the jump ratios of proton density and total magnetic flux density across a shock is described.

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## 1. INTRODUCTION

Among the ten $-$Bz events triggering major geomagnetic storms between August 1978 and December 1979, 8 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 (ICME) [e.g., Hoeksema and Zhao, 1991], 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 $-$Bz 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 literatures. One is the corotating interaction region (CIR) caused by high speed stream-low speed stream interaction. The other interaction region is caused by fast transient flow-low speed stream interaction. To be brief we here call the stream-stream interaction as SS shock pair (or CIR if corotating) and the fast transient flow-slow steady flow (stream) interaction as TS shock pair. 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 11:40 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 Figure 6 of Tsurutani et al., 1988). 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 (Interplanetary Medium Data Book), 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 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 low speed stream and the magnetic field should be the Parker spiral. However existence of large southward IMF components ahead of the forward shock is hard to reconcile with a spiral field. The purpose of the present paper is to search for the causes of the observed shock pair and the $-Bz$ event by first analyzing the magnetic configuration in fast and slow plasma flow. then examining physical properties of the plasma ahead of the forward shock and finally predicting the jump ratio of the total magnetic flux across fast shock and comparing it with observations.

## 2. MAGNETIC CONFIGURATION IN THE 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 around $(\phi, \theta) = (-45°, 0°)$ or $(135°, 0°)$ if the MHD fluctuations are weak; the distribution will be broader if the fluctuations are strong, as in the high speed stream. Here $\phi$ and $\theta$ denote azimuthal (spiral) and latitudinal angles of IMF in the solar ecliptic coordinate system. The azimuthal angle of $-45°$ ($135°$) denotes field polarity of away from (toward) the Sun. A nonspiral field configuration indicates field in a transient flow, e.g., a ICME. 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-average values of the azimuthal and latitudinal angle of the interplanetary magnetic field in the solar ecliptic coordinate system from November 24, 00 UT to November 26, 23 UT, 1978 to determine the angular distributions shown in Figure 1. The time intervals for the five panels from top to bottom in Figure 1 correspond to the five intervals displayed in the top panel of Figure 2. The panels in Figure 1 show the field direction for different parts of the structure: ambient, preshock, post shock before and after the discontinuity, and after the reverse shock. The angular distribution of the field right behind the reverse shock is around (−45°, 0°) with rather wide diffusion, as expected for the high speed stream with strong fluctuations (see panel 5 of Figure 1). The angular distribution for the field ahead of the forward shock shows multiple components (see the panels 1 and 2 of Figure 1). Panel 1 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 (panel 2) is definitely not a spiral field, shown by significant departures from the directions $(-45°, 0°)$ or $(135°, 0°)$, implying that it is field in a transient flow. Panels 3 and 4 of Figure 1 display the angular distributions for fields within the interaction region separated by the discontinuity. The fiffering distributions between the two panels indicate that the discontinuity is a flow interface.

Therefore, the discontinuity within the shock pair is a flow interface, and the slow flow ahead of the interface is probably 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 Sun-Earth line. The shock pair is thus probably caused by high speed stream- slow transient flow interaction (ST shock pair).

## 3. PLASMA PROPERTIES OF THE SLOW FLOW

Let us now examine plasma properties of the slow flow ahead of the forward shock to figure out what the slow flow is. Panel 1 of Figure 2, the proton velocity profile, displays the five intervals of time from left to right, corresponding to the five panels in Figure 1. The vertical dashed, solid and dotted lines in each panels denote the forward shock, flow interface and reverse shock, respectively. The −Bz event studied here is indicated in panel 7. panels 1 - 3 of Figure 2 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].

The profiles of proton temperature, total magnetic flux and velocity indicate that the slow flow with nonspiral field mentioned above is just a Cold Magnetic Enhancement defined by Burlaga et al. [1978] (see panel 3 and 4 of Figure 2 and compare them with panel 1). 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 a ICME.

Gosling et al. [1987] found that counterstreaming flux events of suprathermal electrons (BDE), may be one of the most prominent signatures of coronal mass ejection events in interplanetary space. The field within a BDE tends to be oriented at angles other than along the normal Parker spiral. Independent of whether or not they are shock associated, 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]. In fact a BDE is observed between November 24 20:00 UT and November 25 09:10 UT, 1978 [Gosling et al., 1987] though the time interval is a bit narrower than the Cold Magnetic Enhancement (see panel 2 and panel 3 of Figure 2). Crooker et al. [1990] recently analyzed CME geometry in interplanetary space and found that the radial boundaries of a CME were determined based on 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.

## 4. CONTRIBUTION OF FAST SHOCK TO −Bz 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.

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 $\beta$ 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 $\beta$ 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 $\beta$ values between 0.5 and 5.0. The shock normal seems nearly parallel to the ecliptic because the gas driving the shock is a high speed stream, and the shock angle is likely 50° because the latitudinal angle of field is about 50° ahead of the forward shock (see Figure 1). Based on Figure 3 the total magnetic flux ratio can be inferred to be close to or slightly less than 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,

## 5. CONCLUSION AND DISCUSSION

By analyzing the angular distribution of magnetic field in fast and slow plasma flow, examining plasma properties in the slow flow and comparing it with the bidirectional electron flux event. 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 a ICME centered far away from Sun-Earth line.

2. The slow flow ahead the interface is an ICME.

3. The shock pair associated with the 25 November 1981 −Bz event is caused by a high speed stream-slow ICME interaction;

4. The compression alone appears to be adequate to explain the large value of −Bz observed within the shocked ICME because of the strong upstream field which is the internal field of the ICME.

5. The interface for high speed stream-slow ICME interaction has similar characteristics to that for the high speed stream-low speed stream interaction.

6. There is no large internal field rotation in the slow flow. It is basically a planar structure. The shock pair may be caused by the physical process similar to what causing the formation of CIR if the planar structure parallel to the ecliptic plane (the XY plane of the solar ecliptic coordinate system). If it is the case, we can infer that there should be no significant north-south field component within the shock pair. The inference is not consistent with observations. The another extreme case is that the

planar structure is parallel to the meridinal plane (XZ plane). In this case, a large north-south field component can be expected and the ICME must be disconnected from the Sun. Thus, because the magnetic structure in the slow flow is not a magnetic cloud, the existence of the high speed stream-slow ICME interaction region with large Bz component suggests the existence of a detached ICME from the Sun.

Numerical simulations and in situ observations show [Hundhausen and Gosling, 1976; Smith and Wolf, 1976; Hundhausen, 1985; Gosling et al., 1988] that for high speed stream-low speed stream 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-low speed stream interaction, 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 high speed stream-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 $\beta$ and proton density and total magnetic flux ratios 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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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.

Crooker, N. U., J. T. Gosling, E. J. Smith and C. T. Russell, A bubblelike coronal mass ejection flux rope in the solar wind, *Physics of Magnetic Flux Ropes* ed. by C. T. Russell, E. R. Priest, L. C. Lee, pp. 365–372, American Geophysical Union, Washington DC, 1990.

Farrugia, C. J., M. W. Duniop, F. Geurts, A. Balogh, D. J. Southwood, D. A. Bryant, M. Neugebauer and A. Etemadi, *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* ed. by C. T. Russell, E. R. Priest, L. C. Lee, pp. 343–364, Amerucan Geophysical Union, Washington DC, 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. and D. J. McComas, Field line draping about fast coronal mass ejecta: A source of strong out-of-the-ecliptic interplanetary magnetic fields, *Geophys. Res. Lett., 14*, 355–358, 1987.

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 X. Zhao, Prediction of magnetic orientation in driver gas-associated −Bz events, *J. Geophys. Res.*, in press, 1991.

Hundhausen, A. J., and J. T. Gosling, Solar wind structure at large heliocentric distances: an interpretation of Pineer 10 observations, *J. Geophys. Res., 81*, 1845, 1976.

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

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, 1989.

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

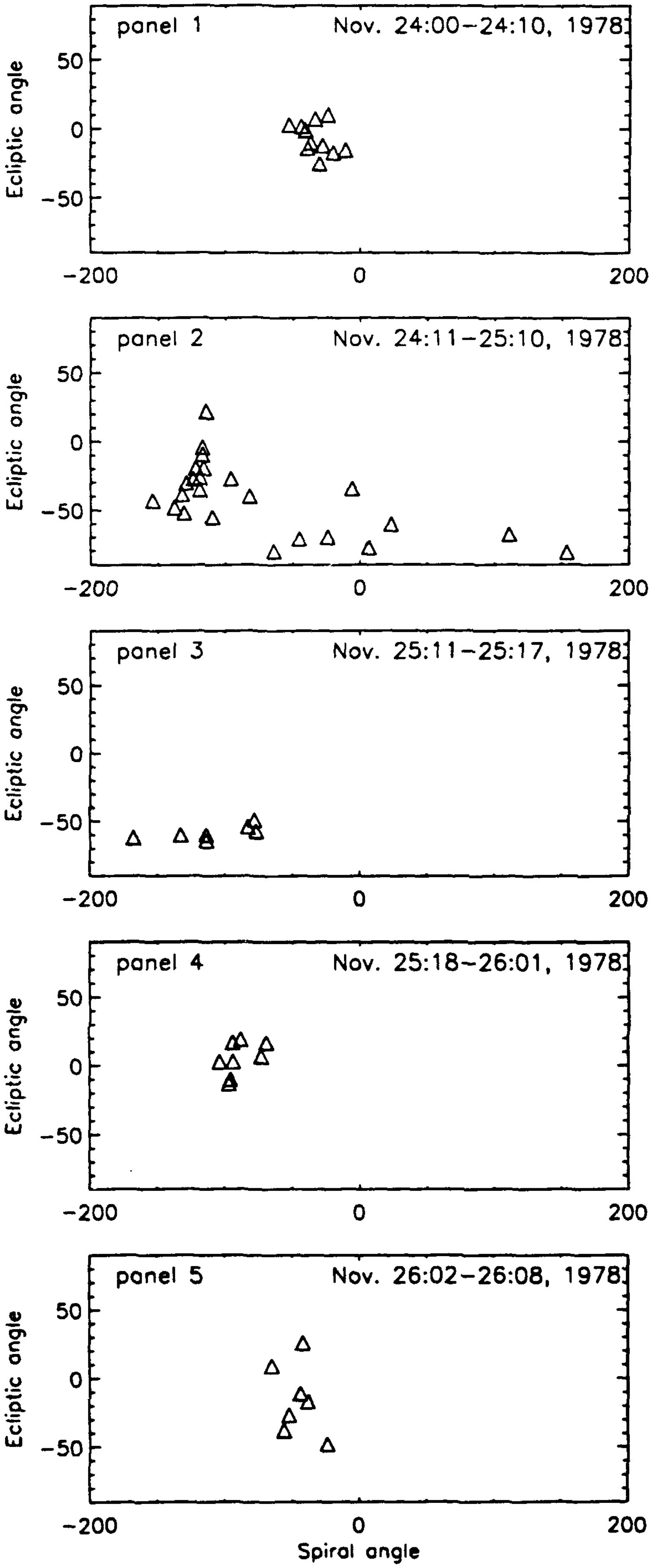
Zhao, X., K. W. Ogilvie and Y. C. Whang, Modeling the effects of fast shocks on solar wind minor ions, *J. Geophys. Res., 96*, 5437–5445, 1991.

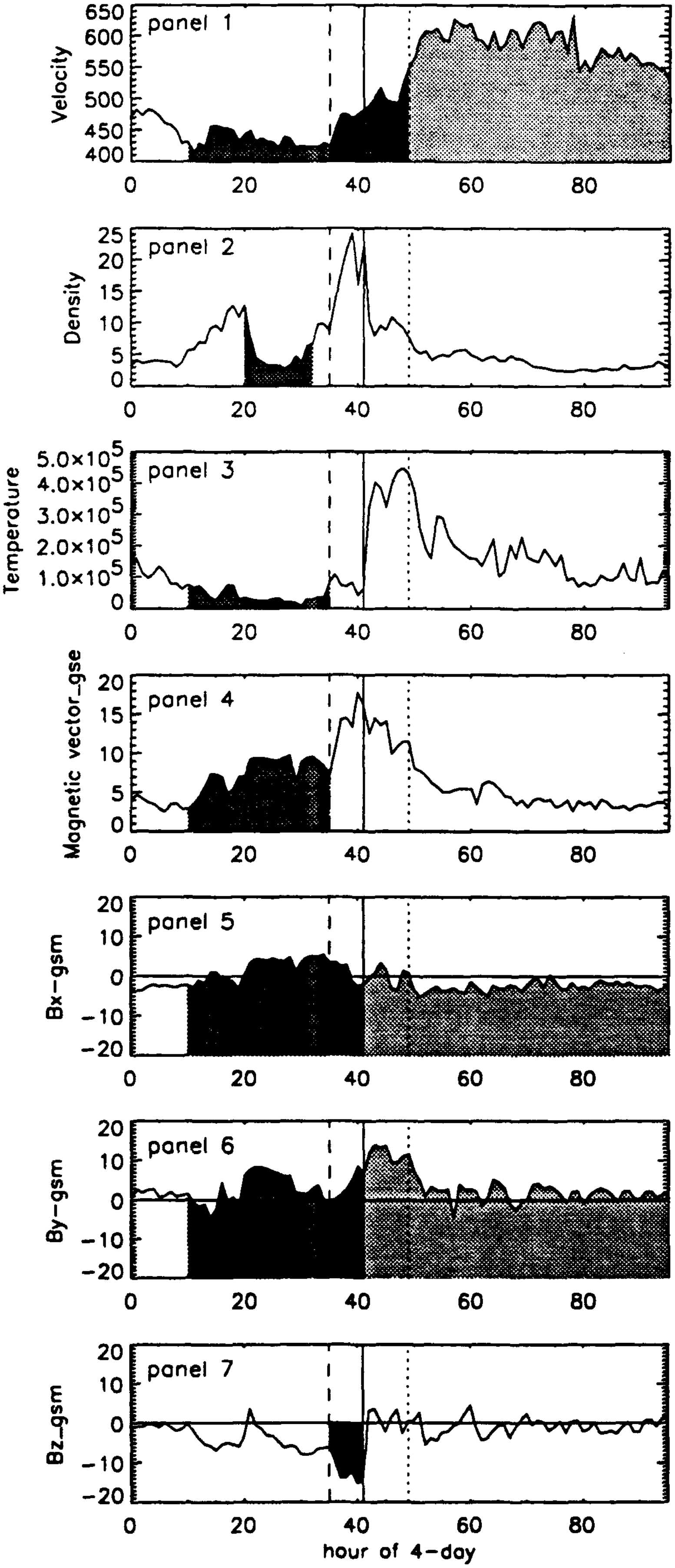
# Captions

Figure 1. Angular distributions of various plasma flows in the solar wind. Panels from 1 to 5 correspond to the field direction for ambient, preshock, post shock before and after the discontinuity, and after the reverse shock.

Figure 2. Profiles of magnetic field and plasma properties between November 24 and November 27, 1978. Panels from top to bottom correspond to flow velocity, proton density, proton temperature, magnetic flux density, and the X, Y and 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.

Figure 3. Dependence of the jump ratio of magnetic flux density on the jump ratio of proton density. The plasma Beta number from top panel to bottom panel 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.


panel 1
Nov. 24:00–24:10, 1978
panel 2
Nov. 24:11–25:10, 1978
panel 3
Nov. 25:11–25:17, 1978
panel 4
Nov. 25:18–26:01, 1978
panel 5
Nov. 26:02–26:08, 1978
Ecliptic angle
50
0
−50
−200
0
200
Spiral angle


panel 1
Velocity
650
600
550
500
450
400
panel 2
Density
25
20
15
10
5
0
panel 3
Temperature
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4.0×10^5
3.0×10^5
2.0×10^5
1.0×10^5
0
panel 4
Magnetic vector_gse
20
15
10
5
0
panel 5
Bx-gsm
20
10
0
-10
-20
panel 6
By-gsm
20
10
0
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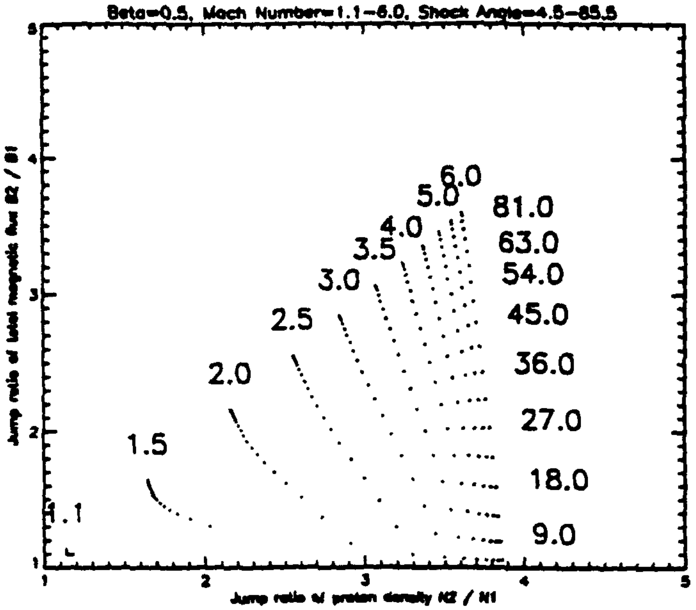
-10
-20
0
20
40
60
80
hour of 4-day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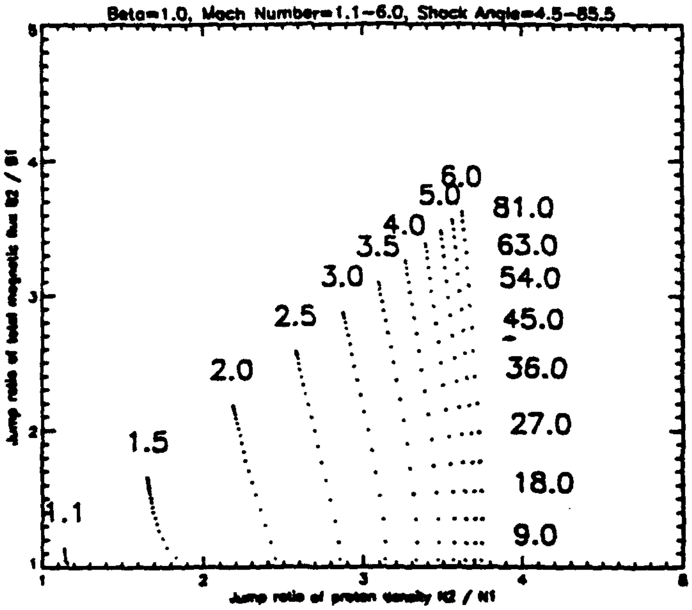
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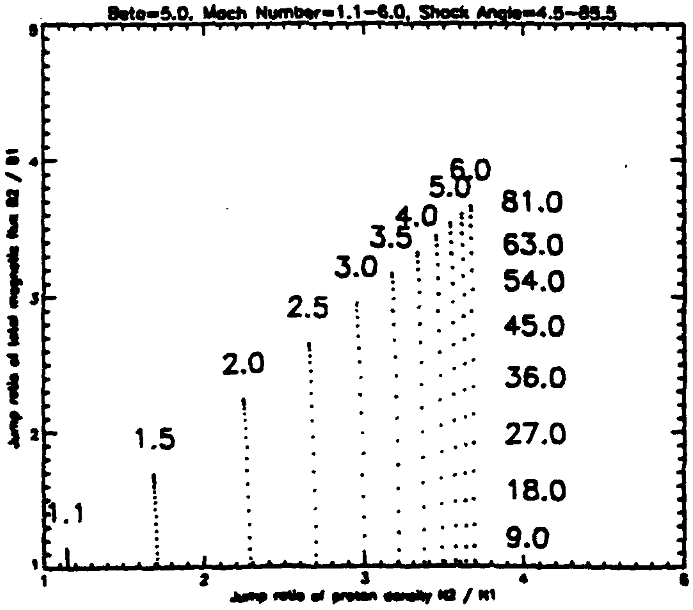
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