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Observations of a switch-off shock in interplanetary space

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[1] An interplanetary slow shock event was observed by Voyager 1 on 1 November 1980. The structure is identified to be a switch-off shock which is a special type of slow shocks by fitting the Rankine-Hugoniot relations. The shock has the following properties: (1) Observed parameters meet the R-H relations well. (2) Number density increases from the upstream region to the downstream region. On the contrary, total magnetic field strength decreases. (3) The slow-mode Mach number is greater than unity in the preshock state and less than unity in the postshock state. (4) The normal Alfvén-Mach number is almost equal to 1 in the preshock state; the tangential component of the downstream magnetic field is "turned off," leaving only a minor quantity along the shock normal.

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1. Introduction

[2] According to the MHD wave theory, there exist three linear MHD waves; they are called fast magnetosonic wave, Alfvén wave (intermediate mode), and slow magnetosonic wave. If we define state 1 as the state whose shock frame fluid velocity is superfast magnetosonic, state 2 whose fluid velocity is subfast magnetosonic and super-Alfvénic, state 3 whose fluid velocity is sub-Alfvénic and superslow magnetosonic, and state 4 whose fluid velocity is subslow magnetosonic, the entropy-satisfying jump relations then include 1→2, 1→3, 1→4, 2→3, 2→4, and 3→4 transitions. The 1→2 and 3→4 shocks are fast and slow shocks, respectively. The other four transitions are called intermediate shocks [*Wu*, 1990]. Rankine-Hugoniot (R-H) relations define the shock jump conditions. Therefore, it is required that all those six types of shocks satisfy the R-H relations. In addition, as the upstream flow velocity is equal to the normal Alfvén speed, the transverse component of the downstream magnetic field vanishes, producing a slow switch-off shock [*Daughton et al.*, 2001]. Since switch-off shocks propagate at the maximum allowable speed for slow shocks, namely, the intermediate speed, the switch-off shock may be regarded as the strongest possible slow shock for a particular plasma condition [*Kantrowitz and Petschek*, 1966]. Switch-off shocks are the limiting cases of 3→4 slow shocks and 2→4 intermediate shocks [*Wu*, 1990].

[3] Slow shocks are believed to play an important role in magnetic reconnection and conversion of energy stored in the magnetic field to plasma thermal energy [*Petschek*, 1964]. In addition, *Lee et al.* [1989] studied the slow shock characteristics in the magnetotail using particle and MHD simulations. The MHD simulations showed that the spontaneous reconnection process in the near-Earth plasma sheet can lead to the formations of switch-off shock. In contrast to fast shocks which are observed frequently in interplanetary space, the reported slow shocks are relatively rare, and only a small number of slow shocks have been observed in interplanetary space [*Chao and Olbert*, 1970; *Burlaga and Chao*, 1971; *Richter et al.*, 1985; *Whang et al.*, 1996, 1998; *Ho et al.*, 1998; *Zuo et al.*, 2006]. However, to our knowledge no one has reported a switch-off shock. Some authors studied the formation and structure of switch-off shocks by numerical simulations [*Swift*, 1983; *Lee et al.*, 1989; *Vu et al.*, 1992; *Daughton et al.*, 2001]. Here we identify an interplanetary switch-off shock detected by Voyager 1 on 1 November 1980 by fitting the R-H relations. In this paper, we report the identification of a switch-off shock observed in interplanetary space.

2. Observations of a Slow Switch-Off Shock

2.1. Method of Analysis

[4] To study an observed shock, it is important to fit measured magnetic fields and plasma on both sides to the R-H relations. The main task of shock fitting is to set up an accurate shock frame of reference. In searching for an accurate shock frame, several methods have been developed to determine the shock normal vector **n**, such as the coplanarity method, the minimum variance analysis (MVA) method and the triangulation method [*Knetter et al.*, 2004]. For an MHD shock, the coplanarity theorem requires the magnetic field vectors $\mathbf{B}_1$ and $\mathbf{B}_2$ in the upstream and downstream regions and the shock normal **n** to be coplanar. The unit shock normal vector can therefore be obtained as follows [*Colburn and Sonnet*, 1966]:

$$\mathbf{n} = \pm \frac{(\mathbf{B}_1 \times \mathbf{B}_2) \times (\mathbf{B}_1 - \mathbf{B}_2)}{|(\mathbf{B}_1 \times \mathbf{B}_2) \times (\mathbf{B}_1 - \mathbf{B}_2)|}. \quad (1)$$

[5] So one can define an orthogonal shock frame of reference, let **q** denote the unit vector normal to the coplanar

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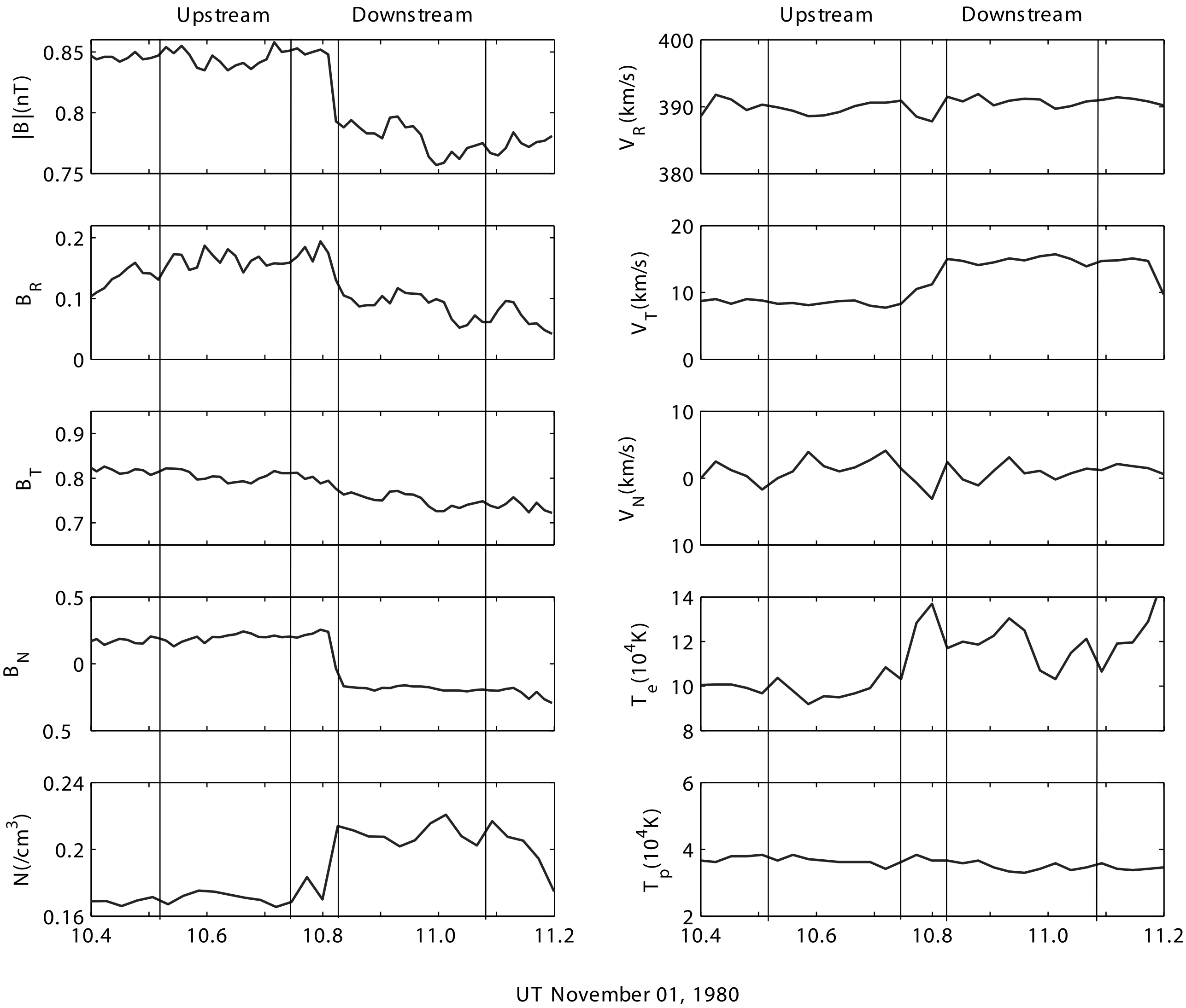

Figure 1. The interplanetary magnetic field and plasma data measured by the Voyage 1 in RTN coordinate system on 1 November 1980. The electron temperature is inferred from R-H relations by use of other measured values.

plane, which can be calculated from $\mathbf{q} = \pm(\mathbf{B}_1 \times \mathbf{B}_2)/(|\mathbf{B}_1 \times \mathbf{B}_2|)$, then define $\mathbf{s} = \mathbf{n} \times \mathbf{q}$. Therefore, the $\mathbf{s}-\mathbf{q}$ plane is just the shock front; thus both the upstream and downstream magnetic fields are in the $\mathbf{n}-\mathbf{s}$ plane.

[6] In the present paper, we apply a new shock fitting procedure proposed recently by *Lin et al.* [2006]. Their method is based on one-fluid anisotropic R-H relations, a Monte Carlo calculation and a minimization technique are used. *Lin et al.* [2006] use the upstream and downstream observed mean variables and associated errors to randomly generate arrays of the variables needed for the fitting procedure, and every generated array for these variables satisfy the R-H relations. Here, each array is generated by using a random number generator function, called Rnd(σ). This function generates an array of normally distributed numbers with an average of zero, and the standard deviation (SD) calculated from these numbers equals to σ. Then a minimization technique are used, with this, a best fit solution that satisfies the R-H relations and that is closest to the data mean is obtained. It should be noted that the total (associated) error consists of the SD and a systematic error that may be due to instruments and/or any other uncertainties. The SD can be calculated directly from the observable array. However, the systematic error is usually unknown; *Lin et al.* [2006] assumed that the systematic error is a half the SD. More detailed descriptions about the procedure are given by *Lin et al.* [2006].

2.2. Identification Based on R-H Relation

[7] This shock was observed at about 1049 UT on 1 November 1980, when Voyager 1 was approximately 9 AU from the Sun. Figure 1 shows the observed magnetic field and plasma data in the orthogonal RTN coordinate, where **R** is along the Sun-spacecraft line and point away from the Sun, **T** is in a plane parallel to the solar equatorial plane and positive in the direction of planetary motion, and **n** completes a right-handed system. The magnetic field data are 48-s average, and plasma data are 96-s average. Since only

Table 1. The Observed and Best Fitting Parameters of the 1 November 1980 Shock-like Discontinuity

Parameter	Observed Values[a]	Best Fitting Values
$\mathbf{B}_1$, nT	(0.149, 0.810, 0.171)	(0.147, 0.808, 0.149)
$\mathbf{B}_2$	(0.102, 0.756, −0.159)	(0.102, 0.766, −0.134)
N_1, N_2, cm^{-3}	0.171, 0.210	0.171, 0.211
$\mathbf{V}_1$, km/s	(390, 8, 1)	(388, 6, −5)
$\mathbf{V}_2$	(391, 15, 1)	(392, 16, 8)
β_1, β_2	1.09, 1.82	1.12, 1.83
$\mathbf{n}$	(0.134, 0.975, −0.180)	(0.130, 0.977, −0.166)
$\mathbf{s}$	(−0.140, −0.161, −0.977)	(−0.155, −0.145, −0.977)
$\mathbf{t}$	(−0.981, 0.156, 0.115)	(−0.979, 0.153, 0.132)
M_{AN1}, M_{AN2}	1.005, 0.906	0.992, 0.893
M_{SL1}, M_{SL2}	1.212, 0.907	1.169, 0.893
N_2/N_1	1.23	1.23
u	−0.062	−0.013
θ_{BN2}	1.44°	0.27°

[a]The SD of $\mathbf{B}_1$ is (0.023, 0.011, 0.027), the SD of $\mathbf{B}_2$ is (0.012, 0.016, 0.038), the SD of N_1 and N_2 are 0.025 and 0.057, the SD of $\mathbf{V}_1$ and $\mathbf{V}_2$ are (3, 2, 5) and (3, 3, 6).

the proton temperature but not the electron temperature is measured, the electron temperature in Figure 1 is inferred from R-H relations by use of other measured values. As *Chao et al.* [1993] pointed out, the R-H relations let us determine any other parameters included in R-H relations if 11 parameters are given. Because 14 observed parameters are available for Voyage 1. Therefore, we can predict the electron temperature. In general, the ratio of electron temperature to proton temperature in interplanetary space is about 1∼10. So the predicted electron temperature is suitable. From Figure 1 it can be seen that the number density N, the electron temperature T_e, the T component of proton velocity (V_T) increased across the discontinuity, while the total magnetic field strength $|B|$ decreased. Here we notice that the proton temperature has no obvious increase, however, the hybrid code simulations also indicate that the growth in ion temperature in shock transition region is very slow for the switch-off shock where there is no chaotic heating of ions [*Lin and Lee*, 1991]. All these jump signatures are consistent with the requirements for a switch-off shock.

[8] The selection of the intervals for the upstream and downstream regions is difficult and important, but it's also rather subjective to confirm these regions as shown in previous studies. Here we try to select the intervals that are relatively stable and are close to the transition layer to avoid the effect of waves as well as the disturbances associated with the other structures.

[9] Table 1 lists the observed data means. These averaged values are then used to study the macroscopic variations of the shock using the R-H relations. Using the observed data means and R-H relations, we derived corresponding shock parameters of this discontinuity, which are listed in Table 1. The derived parameters are the shock normal vector **n**, other two axes of the shock coordinate system **t** and **q**, the plasma beta (β), the normal Alfvén-Mach number ($M_{AN} = V_n/V_A$) and the slow mode Mach number ($M_{SL} = V_n/V_{sl}$) in the upstream/downstream region, the ratio of the downstream to the upstream densities (N_2/N_1) and tangential magnetic fields ($u = B_{s2}/B_{s1}$), the angle, $\theta_{BN2} = \cos^{-1}(\mathbf{B}_2 \cdot \mathbf{n}/B_2)$, of the shock normal with the downstream magnetic field. In the above expression, $V_A = B_n/(\mu_0\rho_1)^{1/2}$ is the Alfvén speed based on the magnetic field component normal to the shock front, V_n is the component of the bulk velocity to the shock front and measured in the shock frame of reference, and V_f and V_{sl} are the speeds of the fast and slow magnetosonic waves in the direction of the shock normal, respectively.

[10] Employing the fitting procedure of *Lin et al.* [2008], we obtain a best fit solution, which satisfies the R-H relations. Table 1 lists the best fit values which are the corresponding parameters calculated from the fitting values. Figure 2 gives the magnetic field and velocity profiles in the shock coordinate system. From Table 1 and Figure 2, we found that this discontinuity has the following properties:

[11] 1. The fitting values are in very good agreement with the observed values, namely, the observed parameters meet the R-H relations well.

[12] 2. The density increases from the upstream region to the downstream region. On the contrary, the total magnetic field strength decreases.

[13] 3. The slow mode Mach number is greater than unity in the preshock state and less than unity in the postshock state.

[14] 4. The normal Alfvén-Mach number (M_A) is almost equal to unity in the preshock state.

[15] The tangential component of the downstream magnetic field is "switched off", leaving only a minor quantity along the shock normal (see Figure 2). Both the ratio of downstream to upstream tangential magnetic fields (u) and the angle (θ_{BN2}) between the shock normal and the downstream magnetic field are very small (see Table 1). Therefore the discontinuity has all the properties of slow switch-off shocks, and we conclude that the discontinuity may be a switch-off shock. In addition, *Kantrowitz and Petschek* [1966] discussed the density ratio across switch-off shocks using a_1^2/b_1^2 ($\gamma\beta_1$), where $a_1^2 = \frac{\gamma P}{N}$, $b_1^2 = \frac{B^2}{2\mu_0 N}$, P is thermal pressure, μ_0 is the permeability of medium. So a_1^2/b_1^2 can be regarded as defining the ratio of upstream gas to magnetic pressure. For $a_1^2/b_1^2 > 1$, switch-off shocks are relatively weak and the density ratio is also relatively insensitive to a_1^2/b_1^2, the density ratios always approach unity. For $a_1^2/b_1^2 < 1$, switch-off shocks is relatively strong, the density ratios increase quickly with a_1^2/b_1^2 descending (the limiting density ratio is 4). As for the observed switch-off shock, take $\gamma = \frac{5}{3}$, $a_1^2/b_1^2 = 1.87 > 1$, so the event is a relatively weak switch-off shock. Furthermore, its density ratios is only 1.23 (see Table 1). Although the observed switch-off shock is relatively weak, the background solar wind is more stable and only has some weak disturbances (see Figure 2, left). So it is still easy to recognize this discontinuity from the background solar wind by eye.

3. Summary and Discussions

[16] In the past more than four decades, there are a large number of investigations for interplanetary slow shocks, and a small number of slow shocks have been observed in interplanetary space. In this study, an interplanetary switch-off shock is identified by fitting the R-H relations. This switch-off shock was observed by Voyager 1 on 1 November 1980. We fitted this discontinuity using the procedure of *Lin et al.* [2008] and found that the observed

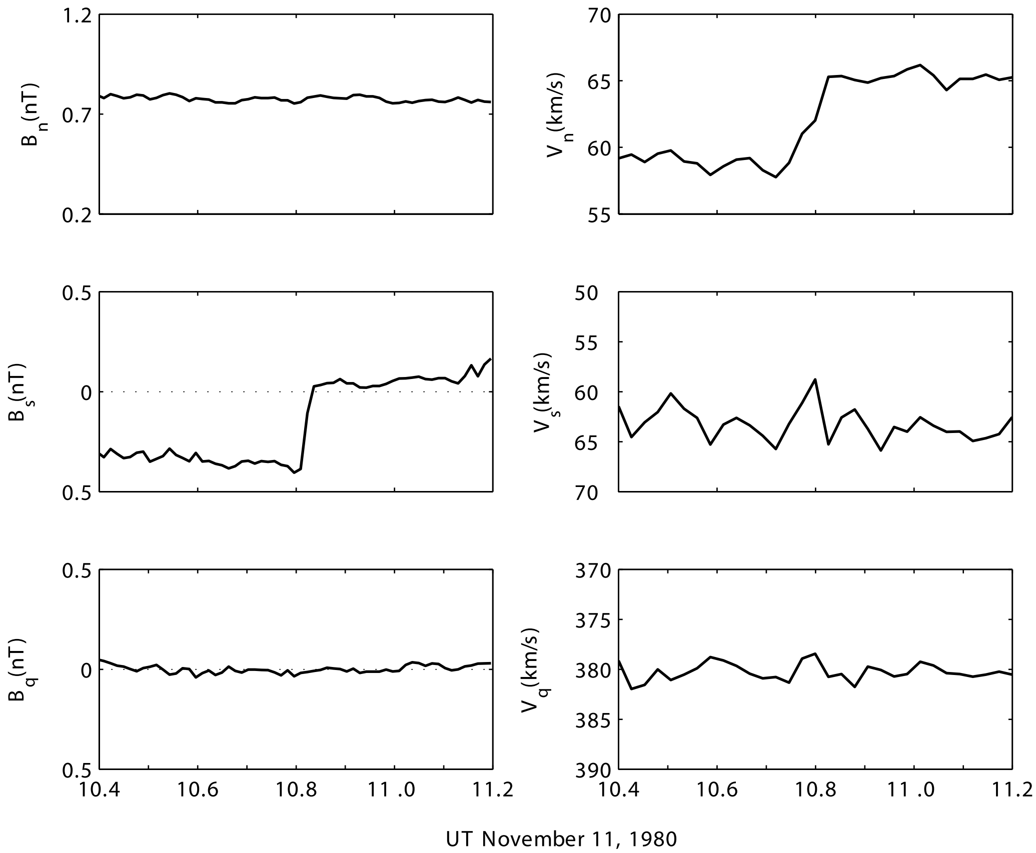

Figure 2. The observed magnetic fields and proton velocity on 1 November 1980 in the shock coordinate system.

magnetic field and plasma data satisfy the R-H relations well. The normal component of the bulk velocity to the shock front is larger than the local slow magnetoacoustic speed and almost equal to the local normal Alfvén speed in the upstream region, and in the downstream region the corresponding normal velocity is smaller than the local slow magnetoacoustic speed. The tangential component of the downstream magnetic field is switched off, leaving only a weak component along the shock normal. In addition, the proton temperature has no obvious increase, which agrees with the hybrid code simulations results [*Lin and Lee*, 1991]. Namely the observations of this discontinuity satisfy all the criteria of a slow shock and close to a switch off shock. So we believe that this event is a switch-off shock.

[17] In addition, as our previous study [*Feng et al.*, 2007] pointed out, there exist ambiguity between slow shocks and tangential discontinuities (TDs) when one determined the discontinuity type based on one spacecraft observations. The ambiguity can be solved if multispacecraft observations are available. For this discontinuity, the only one spacecraft-Voyage 1 is available. Therefore, we cannot confirm this discontinuity by multispacecraft. However, this is the first switch-off shock discovered in interplanetary space.

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