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Observations of an interplanetary switch-on shock driven by a magnetic cloud

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[1] A possible interplanetary switch-on shock event prior to a trailing magnetic cloud was observed on August 1, 2002 at 1 AU. We fit the data with the Rankine-Hugoniot (R-H) relations based on both oblique and switch-on shock models. It is found that both models are consistent with the observed data, and the best fit solutions of the two models are close to one another. For the oblique shock model, the best fit upstream shock normal angle, θ_{BN1} (= $\cos^{-1}(B_{t1}/B_1)$), is as small as 5.55°. The shock has the following characteristics: (1) plasma density, plasma temperature, and the magnetic field strength all increase across the shock, (2) protons are thermalized very efficiently across the shock, but it is not the case for electrons, (3) the fast-mode Mach number is greater than unity in the preshock region and less than unity in the postshock region, and (4) from the oblique shock model we find that the normal Alfvén Mach number is very close to unity in the postshock region, while from the switch-on shock model we obtain a solution of unity normal Alfvén Mach number. Our results clearly demonstrate the MHD character of a fast shock propagating along the ambient magnetic field. **Citation:** Feng, H. Q., C. C. Lin, J. K. Chao, D. J. Wu, L. H. Lyu, and L. C. Lee (2009), Observations of an interplanetary switch-on shock driven by a magnetic cloud, *Geophys. Res. Lett.*, *36*, L07106, doi:10.1029/2009GL037354.

1. Introduction

[2] According to the ideal MHD theory, there exist three types of linear MHD wave: fast magnetosonic, Alfvén (intermediate), and slow magnetosonic waves. If we define state 1 as the state upon which the fluid velocity is super-fast–magnetosonic, state 2 upon which the fluid velocity is sub-fast–magnetosonic and super-Alfvénic, state 3 upon which the fluid velocity is sub-Alfvénic and super-slow–magnetosonic, and state 4 upon which the fluid velocity is sub-slow–magnetosonic, the entropy-satisfying jump relations then include $1 \rightarrow 2$, $1 \rightarrow 3$, $1 \rightarrow 4$, $2 \rightarrow 3$, $2 \rightarrow 4$, and $3 \rightarrow 4$ transitions. The $1 \rightarrow 2$ and $3 \rightarrow 4$ shocks are fast and slow shocks, respectively. The other four transitions are called intermediate shocks [*Wu*, 1990]. 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 switch-off shock [*Daughton et al.*, 2001; *Feng et al.*, 2008]. Thus, switch-off shock is an extreme of the $3 \rightarrow 4$ slow shock and $2 \rightarrow 4$ intermediate shock [*Wu*, 1990]. In contrary to the switch-off shock, a switch-on shock has a vanished transverse component of the upstream magnetic field, and on its downstream side the flow speed is equal to the normal Alfvén speed. Switch-on shock is an extreme of the $1 \rightarrow 2$ fast shock and $1 \rightarrow 3$ intermediate shock.

[3] From the Rankine-Hugoniot (R-H) relations, the switch-on shock solution can be obtained in a narrow range of the upstream parameters. When the upstream region has a very low beta plasma ($\beta \ll 1$) with an adiabatic condition (γ = 5/3), a parallel shock will generate a non-zero downstream tangential magnetic field with $1 < M_A < 2$. Here, M_A is the Alfvén Mach number ($M_A = V_1/V_A$, where V_1 is the upstream velocity seen in the shock frame). Beyond this range, the parallel shock is purely hydrodynamic; the downstream magnetic field does not 'switch-on'. For higher beta plasma, the possibility of the existence of a switch-on shock becomes lower [*Kantrowitz and Petschek*, 1966; *De Sterck and Poedts*, 1999]. However, in the two-fluid model, if one considers the electron heat conduction, the range for the switch-on shock solution can be extended [*Kennel and Edmiston*, 1988].

[4] A switch-on shock propagates parallel to ambient magnetic fields. From the linear wave theory, it is known that magnetic compression cannot happen in the direction exactly parallel to the background magnetic field. However, if one considers second-order perturbation, the compression can then occur [*Omidi et al.*, 1990]. Switch-on shock is expected to form from linearly-polarized Alfvénic wave train. Some authors argue that if the leading wave disturbs the ambient magnetic field and produces a tiny nonzero transverse magnetic field, then the trailing wave can propagate in a slightly oblique direction relative to the magnetic field. In such a condition, the magnetic field can be compressed [*Kantrowitz and Petschek*, 1966; *Kennel and Edmiston*, 1988]. The existence of switch-on shocks have been confirmed in numerical simulations [e.g., *Kan and Swift*, 1983; *Omidi et al.*, 1990].

[5] A switch-on shock is expected to develop as a low Alfvén Mach number (between 1 to 2) shock in a low beta plasma and likely to be observed in interplanetary space [*Kennel and Edmiston*, 1988]. If a fast CME moves from the sun in a low-beta corona, it may induce a switch-on shock at some magnetic field topology [*De Sterck et al.*, 1998]. To our knowledge, a switch-on shock has been reported as a part of Earth's bow shock [*Farris et al.*, 1994]. However, no switch-on shock preceding a CME has been reported to date. In this paper, we report a switch-on

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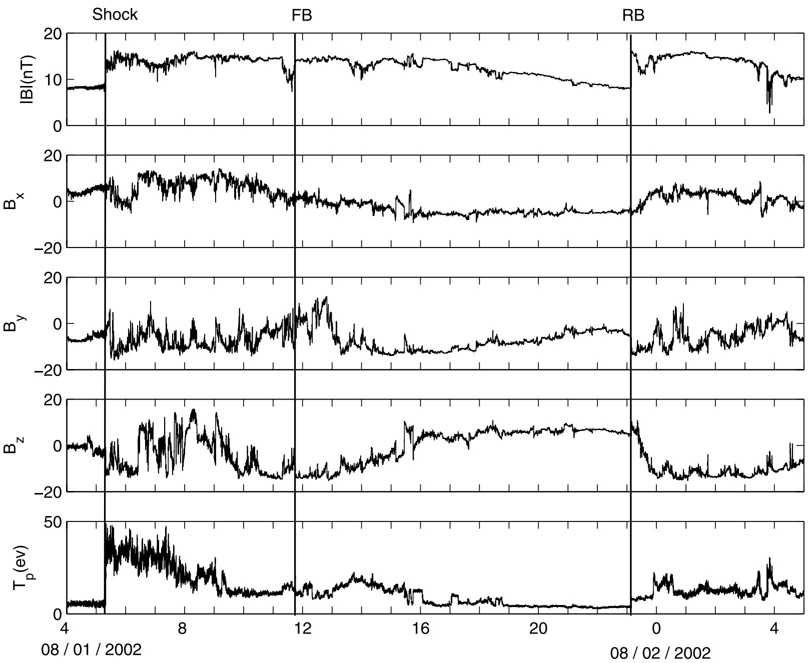

Figure 1. Interplanetary magnetic field and proton temperature data measured by the Wind spacecraft during the 1–2 August 2002 Magnetic cloud passages. FB and RB are the estimated front and rear boundaries, respectively.

shock prior to a magnetic cloud. The shock was observed by Wind at 1 AU on August 1, 2002. It has a low upstream plasma beta ($\beta < 0.2$).

2. Observations of a Switch-on Shock

2.1. Data and Method of Analysis

[6] In the analysis, we consider the contributions of both the protons and alpha particles to the plasma mass. The magnetic field data are obtained from the Magnetic Field Investigation (MFI) magnetometer, and the proton, electron and alpha particle data are obtained from the 3-Dimension Plasma (3DP) analyzer. Description of the instruments on board Wind is given by *Lepping et al.* [2005] and *Lin et al.* [1995]. The data have a time resolution of 3 s except in the case of electron data where a 92-second average is used.

[7] For an ideal MHD shock, the coplanarity theorem requires that the up- and down-stream magnetic fields ($\mathbf{B}_1$ and $\mathbf{B}_2$) and the shock normal vector $\mathbf{n}$ lie on a coplanar plane. The shock normal vector can therefore be obtained as follows [*Colburn and Sonnet*, 1966]:

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

On the basis of it, one can define an orthogonal shock coordinate system. Provided that $\mathbf{s}$ denotes a unit vector perpendicular to the coplanar plane, it can be obtained by $\mathbf{s} = \pm(\mathbf{B}_1 \times \mathbf{B}_2)/|(\mathbf{B}_1 \times \mathbf{B}_2)|$. Thus, the third coordinate, $\mathbf{t}$, can be obtained from $\mathbf{t} = \pm\mathbf{n} \times \mathbf{s}$. As a result, the $\boldsymbol{t} - \boldsymbol{s}$ plane is just the shock front, and both the up- and down-stream magnetic fields lie on the $\boldsymbol{n} - \boldsymbol{t}$ plane.

[8] To study an observed shock, it is important to fit the measured magnetic fields and plasma data on both sides of the shock to the R-H relations. The main task of shock fitting is to find a reliable shock frame of reference. In searching for a shock frame, identification of shock normal vector, $\boldsymbol{n}$, is crucial. Here we apply a shock fitting procedure based on the Monte Carlo calculation proposed recently by *Lin et al.* [2006]. The procedure finds optimized (best fit) shock coordinates ($\mathbf{n}$, $\mathbf{t}$, and $\mathbf{s}$). *Viñas and Scudder* [1986] had proposed a least-squares approach to determine an optimized shock normal vector using a subset of the R-H relations. The approach was then modified by *Szabo* [1994] to include the whole set of the R-H relations. The Monte Carlo shock fitting (MSF) procedure also considers the whole set of the R-H relations. The numerical scheme of the MSF procedure is different from that of *Viñas and Scudder* [1986]. Moreover, with the procedure the tangential vector of shock can simultaneously be found together with the shock normal vector. The shock tangential vector plays a more role for MHD shocks than for hydrodynamic shocks, since for the MHD shock, the plasma flow is deflected toward the shock tangential direction. More detailed descriptions about the MSF procedure are given by *Lin et al.* [2006].

2.2. Identification Based on the R-H Relations

2.2.1. Estimate of the Shock Using Oblique Shock Model

[9] The shock was observed by Wind at ~0519:28 UT on August 1, 2002, when Wind was located at (20.9, 86.5, 4.8) R_E in the GSE coordinate system. The shock is found prior to a magnetic cloud, and it may be a product in the leading medium as the medium is pushed and compressed by the trailing magnetic cloud. A magnetic cloud is defined empirically in terms of its magnetic field and plasma having the following properties: (1) a high magnetic field strength compared to the ambience, (2) a smooth change in field direction as observed by a spacecraft passing through the cloud, and (3) a low proton temperature compared to the ambient proton temperature [*Burlaga et al.*, 1981; *Burlaga*,

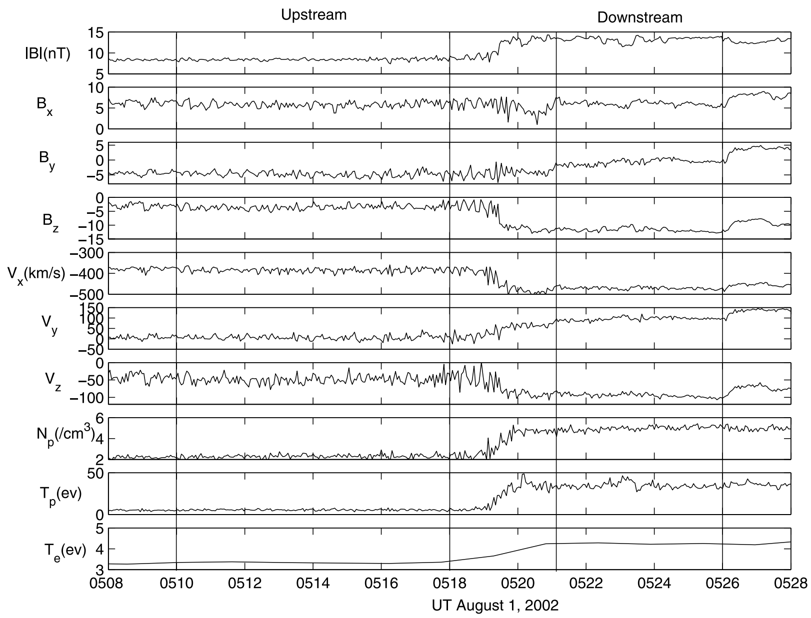

Figure 2. The interplanetary magnetic field and plasma data measured by Wind in GSE coordinate system on 1 August 2002.

1991]. Figure 1 shows the magnetic field and proton temperature data of the magnetic cloud as well as the leading shock. It can be seen that the event satisfies the three criterions mentioned above. In addition, this event was identified as a magnetic cloud by R. P. Lepping et al. (http://lepmfi.gsfc.nasa.gov/mfi/mag_cloud_pub1.html), *Jian et al.* [2006], *Lepping et al.* [2005], *Wu et al.* [2006], *Wu and Lepping* [2007]. Figure 2 shows 13 minutes of the magnetic field and plasma data of this shock observed by Wind. From top to bottom the panels show the magnitude of the total magnetic field (|B|), the x, y, z components of the magnetic field (B_x, B_y, B_z), the x, y, z components of the proton speed (V_x, V_y, V_z), the proton density (N_p), the proton and electron temperatures (T_p), respectively. It can be seen from Figure 2 that the proton number density N_p, the proton and electron temperatures T_p and T_e, and the total magnetic field strength $|B|$ increase across the discontinuity. As can also be seen, the protons are thermalized to a very high temperature across the shock in comparison to the unperturbed state. However, it is not the case for the electrons. In addition, across the shock the proton velocity $|V|$ (not shown here) also increases by 112 km/s. All these jump signatures are consistent with the requirements for a fast shock.

[10] The selected up- and down-stream intervals for fitting are indicated by the vertical lines in Figure 2. The selection of the intervals representative of the up- and down-stream regions is difficult and important, and a certain amount of subjectivity seems unavoidable. We try to select the intervals which are close to the transition layer and in which the magnetic field and plasma are relatively stable in order to reduce the effect of waves as well as the disturbances associated with the other structures.

[11] Table 1 lists the observed mean values and standard deviations of the magnetic field vector $\boldsymbol{B}$, the solar wind velocity vector $\boldsymbol{V}$, and the number density N. Subscripts 1 and 2 refer to the up- and down-stream variables, respectively. Note that the density N is an effective plasma number density calculated from $N = N_p + 4N_a$, where N_p is the proton number density and N_a is the number density of alpha particles. From the optimized solution obtained by the MSF procedure, we have the corresponding shock parameters. They are listed in Table 1. These parameters are the

Table 1. Observed and Model Solution of the 1 August 2002 Discontinuity Event

Parameter	Observed Values[a]	Fast Shock Model Solution	Switch-on Shock Model Solution
$\mathbf{B}_1$ (nT)	(5.79, −4.88, −3.36)	(6.69, −4.77, −3.36)	(6.84, −4.36, −3.76)
$\mathbf{B}_2$	(5.98, −0.66, −11.76)	(6.17, −1.01, −12.22)	(5.45, −1.30, −11.75)
N_1, N_2 (cm^{-3})	3.30, 7.18	3.11, 7.13	3.25, 6.99
$\mathbf{V}_1$ (km/s)	(−385.3, 4.8, −47.4)	(−385.1, 5.6, −48.8)	(−385.1, 5.6, −48.8)
$\mathbf{V}_2$ (km/s)	(−471.5, 96.3, −94.8)	(−464.6, 91.7, −88.2)	(−467.9, 78.1, −82.5)
β_1, β_2	0.167, 0.652	0.161, 0.695	0.154, 0.624
n	(−0.701, 0.643, 0.308)	(−0.762, 0.578, 0.291)	(−0.765, 0.488, 0.421)
t	(0.019, 0.449, −0.893)	(−0.054, 0.390, −0.919)	(−0.232, 0.400, −0.887)
s	(−0.713, −0.620, −0.327)	(−0.644,−0.717,−0.266)	(−0.601, −0.776, −0.193)
M_{AN1}, M_{NA2}	1.559, 1.062	1.608, 1.063	1.465, 1.000
M_{F1}, M_{F2}	1.549, 0.592	1.600, 0.577	1.465, 0.594
θ_{BN1}	6.40°	5.55°	0.00°

[a]The SD of $\mathbf{B}_1$ is (0.72, 0.96, 0.88), the SD of $\mathbf{B}_2$ is (0.51, 0.88, 0.70), the SD of N_1 and N_2 are 0.23 and 0.33, the SD of $\mathbf{V}_1$ and $\mathbf{V}_2$ are (11.3, 12.5, 12.6) and (6.0, 8.2, 5.2),the SD of β_1 and β_2 are 0.014 and 0.127.

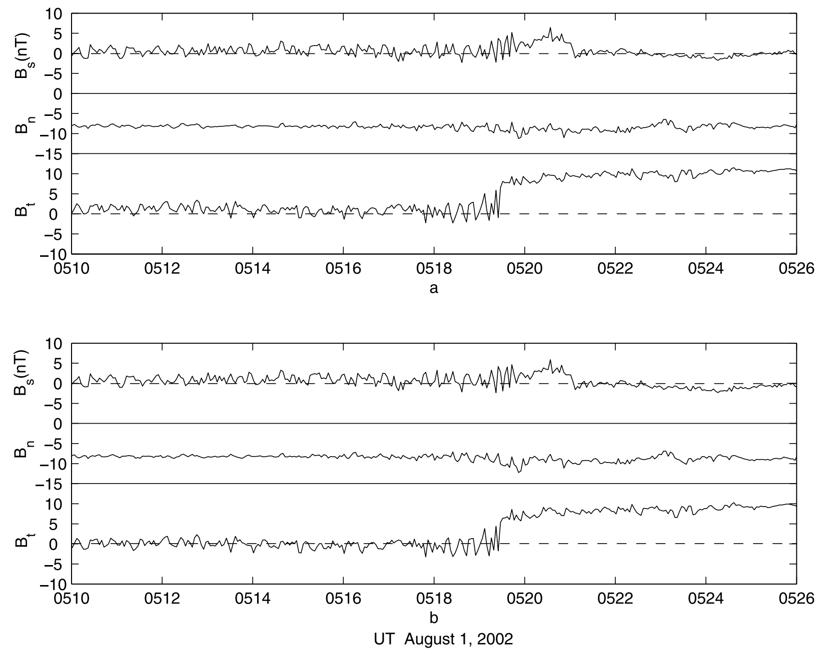

Figure 3. The observed magnetic fields on 1 August 2002 in the shock coordinate system, (a) the fast shock model, and (b) the switch-on model.

shock normal vector $\boldsymbol{n}$, the other two axes of the shock coordinate system $\boldsymbol{t}$ and $\boldsymbol{s}$, the plasma beta (β), the normal Alfvén-Mach number ($M_{AN} = V_n/V_A$), the fast-mode Mach number ($M_F = V_n/V_f$) in the upstream/downstream region, and the shock normal angle, $\theta_{BN1} = cos^{-1}(\boldsymbol{B_1} \bullet \boldsymbol{n}/B_1)$, between the shock normal and the upstream magnetic field vector. Here, $V_A = B_n/(\mu_0\rho)^{1/2}$ is the Alfvén speed based on the magnetic field component normal to the shock front, V_n is the normal component of the bulk velocity to the shock front and measured in the shock frame of reference, and V_f is the speed of the fast-magnetosonic wave in the direction of the shock normal.

[12] As can be seen in Table 1, the best fit values are close to the observed means, namely, the data can be interpreted as an oblique fast shock (with small shock normal angle). The shock solution demonstrates the following properties: (1) the fast-mode Mach number is greater than unity in the preshock state and less than unity in the postshock state, (2) the normal Alfvén-Mach number (M_{AN}) is greater than unity in the preshock state and almost equal to unity in the postshock state, and (3) the shock normal angle (θ_{BN1}) is very small. Figure 3a shows the magnetic field profiles in the shock coordinates. It can be seen that the tangential component of the upstream magnetic field (B_t) is nearly vanished. However, across the shock the tangential component of the magnetic field is "switched-on" significantly. In addition, it can also be seen that the normal component (B_n) is nearly constant across the shock, while the other component (B_s) is nearly zero.

2.2.2. Estimate of the Shock Using the Switch-on Model

[13] In order to have a more comprehensive understanding of whether the shock is switch-on or not, we modify the MSF procedure based on a switch-on model, and we apply it to analyze the data independently. For a switch-on shock, the shock normal is parallel to the upstream magnetic field. Therefore, in the modified procedure, we calculate the shock normal by

$$\mathbf{n} = \pm\mathbf{B}_1/|\mathbf{B}_1| \tag{2}$$

with the Monte Carlo calculation. Therefore, we have a zero degree shock normal angle, θ_{BN1}. The other two coordinates are then obtained by

$$\mathbf{s} = \pm\mathbf{B}_1 \times \mathbf{B}_2/|\mathbf{B}_1 \times \mathbf{B}_2|, \text{ and } \mathbf{t} = \pm\mathbf{n} \times \mathbf{s}. \tag{3}$$

Here, $\mathbf{t}$ represents the tangential direction of the shock.

[14] For a switch-on shock, u ($\equiv B_{t1}/B_{t2}$) $\rightarrow \infty$ and $\theta_{BN1} = 0°$, there are some uncertain situations in the values of the calculated velocity and plasma betas in equations (8) to (11) of *Lin et al.* [2006]. The expressions of these parameters should be modified to

$$\mathbf{W} = M_{AN}V_A(1-y)\hat{n} + M_{AN}V_A y\left(m^2-1\right)^{1/2}\hat{t}, \tag{4}$$

$$\beta_2 = \frac{1}{m^2}\left\{\beta_1 - \left[2(y-1)M_{AN}^2 + \frac{1}{3}(2\xi_2+1)\left(m^2-1\right) - \frac{4}{3}(\xi_2-\xi_1)\right]\right\}, \tag{5}$$

$$(1-y)\beta_1 = \left[\frac{2}{5}\left(m^2-5\right)y^2 + 2y - \frac{2}{5}\right]M_{AN}^2 + \left[\frac{1}{5}(1-6\xi_2)\left(m^2-1\right) + \frac{4}{15}(3\xi_2-5\xi_1+2)\right]y + \frac{8}{15}(\xi_1-1), \tag{6}$$

$$\text{where} \quad M_{AN} = y^{-1/2}, \text{ and } m = \frac{B_2}{B_1}. \tag{7}$$

Since in the modified procedure the shock normal is not obtained by the magnetic coplanarity theorem, the normal magnetic fields $\mathbf{B}_1 \cdot \mathbf{n}$ and $\mathbf{B}_2 \cdot \mathbf{n}$ do not have to be equal to one another. For finding an optimized solution for the divergence free condition of the magnetic field, we add a term in the loss function for the normal magnetic field. The term is expressed as $\left(\frac{B_{2n}-B_{1n}}{\sigma_{bn}}\right)^2$. Here, we calculate the error, σ_{bn}, using the standard errors of the up- and down-stream magnetic field. It is calculated as

$$\sigma_{bn} = \left[\left(\sigma_{b1x}^2 + \sigma_{b1y}^2 + \sigma_{b1z}^2 + \sigma_{b2x}^2 + \sigma_{b2y}^2 + \sigma_{b2z}^2\right)\Big/6\right]^{1/2}. \quad (8)$$

[15] Employing the modified fitting procedure, we obtain a best fit solution which satisfies the R-H relations for a switch-on shock. Table 1 lists the best fit shock parameters. In addition, Figure 3b shows the magnetic field profiles in the optimized switch-on shock coordinates. As can be seen in Table 1 and Figure 3, the solution of this modified procedure is close to the data as well. We also find that the solutions of the two independent analyses based on oblique and switch-on shocks are close to one another. Therefore, we suggest that the spacecraft may have observed a switch-on shock.

3. Summary and Discussion

[16] In this study, an interplanetary switch-on shock is identified by fitting the R-H relations. This shock was observed by Wind on August 1, 2002 at 1 AU. The shock is found prior to a magnetic cloud. We investigate this shock using two independent analyses. For one analysis, we apply the MSF procedure for oblique shock proposed by *Lin et al.* [2006]. For the other one, we also apply the MSF procedure but based on the switch-on shock model. We find that the two models can fit the observed data well, and their solutions are close to one another. The observed magnetic field and plasma data satisfy the R-H relations well. We believe that this event is a switch-on shock.

[17] The upstream parameters of this shock are within the domain of switch-on shock expected by the ideal MHD regime. This shock has a low upstream plasma beta of less than 0.2 ($\beta_1 = 0.154$). The fast and Alfvén Mach numbers are 1.465, which is at a mid point of the theoretical Mach-number domain for a switch-on shock (1–2 for low beta case). Note that here for $\theta_{\mathrm{BN1}} = 0°$, the characteristic speeds of fast and Alfvén mode are equal. Therefore, a switch-on shock has the same upstream fast and Alfvén Mach number. In addition, the downstream normal Alfvén Mach numbers calculated by the two models are unity to almost unity, respectively, which also agrees with the criterion of a switch-on shock. In our analysis, we find that this shock propagates and is compressed in the direction of (−0.77, 0.49, 0.42) (GSE), which is in the direction of the spiral IMF at 1 AU. If the compression is made by the following magnetic cloud, geometrically the shock front should be at the limb side of the whole magnetic cloud structure. The association of the switch-on shock and the CME is an interesting problem and can be investigated in future.

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References

Burlaga, L. F. (1991), Magnetic clouds, in *Physics of the Inner Heliosphere II: Particles, Waves, and Turbulence*, edited by R. Schwenn and E. Marsch, pp. 1–19, Springer, New York.

Burlaga, L., E. Sittler, F. Mariani, and R. Schwenn (1981), Magnetic loop behind an interplanetary shock: Voyager, Helios, and IMP 8 observations, *J. Geophys. Res.*, *86*, 6673–6684.

Colburn, D. S., and C. P. Sonnet (1966), Discontinuity in the solar wind, *Space Sci. Rev.*, *5*, 439.

Daughton, W., D. Winske, and L. Yin (2001), Fully kinetic simulations of slow-mode shocks, in *Proceedings of ISSS-6*, edited by J. Büchner, C. T. Dum, and M. Scholer, p. 236, Schaltungsdienst Lange, Berlin.

De Sterck, H., and S. Poedts (1999), Field-aligned magnetohydrodynamic bow shock flows in the switch-on regime, *Astron. Astrophys.*, *343*, 641–649.

De Sterck, H., B. C. Low, and S. Poedts (1998), Complex magnetohydrodynamic bow shock topology in field-aligned low-β flow around a perfectly conducting cylinder, *Phys. Plasmas*, *5*, 4015–4027.

Farris, M. H., C. T. Russell, R. J. Fitzenreiter, and K. W. Ogilvie (1994), The subcritical, quasi-parallel, switch-on shock, *Geophys. Res. Lett.*, *21*, 837–840.

Feng, H. Q., C. C. Lin, J. K. Chao, D. J. Wu, L. H. Lyu, and L. C. Lee (2008), Observations of a switch-off shock in interplanetary space, *J. Geophys. Res.*, *113*, A05216, doi:10.1029/2007JA012864.

Jian, L., et al. (2006), Property of interplanetary coronal mass ejections at one AU during 1995–2004, *Sol. Phys.*, *239*, 393–436.

Kan, J. R., and D. W. Swift (1983), Structure of the quasi-parallel bow shock: Result of numerical simulation, *J. Geophys. Res.*, *88*, 6919–6925.

Kantrowitz, A., and H. E. Petschek (1966), MHD characteristics and shock waves, in *Plasma Physics in Theory and Application*, edited by W. B. Kunkel, pp. 147–199, McGraw-Hill, New York.

Kennel, C. F., and J. P. Edmiston (1988), Switch-on shocks, *J. Geophys. Res.*, *93*, 11,363–11,373.

Lepping, R. P., C.-C. Wu, and D. B. Berdichevsky (2005), Automatic identification of magnetic clouds and cloud-like regions at 1AU: Occurrence rate and other properties, *Ann. Geophys.*, *23*, 2687–2704.

Lin, C. C., J. K. Chao, L. C. Lee, L. H. Lyu, and D. J. Wu (2006), A new shock fitting procedure for the MHD Rankine-Hugoniot relations for the case of small He^{2+} slippage, *J. Geophys. Res.*, *111*, A09104, doi:10.1029/2005JA011449.

Lin, R. P., et al. (1995), A three-dimensional plasma and energetic particle investigation for the wind spacecraft, *Space Sci. Rev.*, *71*, 125–153.

Omidi, N., K. B. Quest, and D. Winske (1990), Low Mach number parallel and quasi-parallel shocks, *J. Geophys. Res.*, *95*, 20,717–20,730.

Szabo, A. (1994), An improved solution to the "Rankine-Hugoniot" problem, *J. Geophys. Res.*, *99*, 14,737–14,746.

Viñas, A. F., and J. D. Scudder (1986), Fast and optimal solution to the "Rankine-Hugoniot problem", *J. Geophys. Res.*, *91*, 39–58.

Wu, C.-C. (1990), Formation, structure, and stability of MHD intermediate shocks, *J. Geophys. Res.*, *95*, 8149–8175.

Wu, C.-C., and R. P. Lepping (2007), Comparison of the characteristics of magnetic clouds and magnetic cloud-like structures for the events of 1995–2003, *Sol. Phys.*, *242*, 159–165.

Wu, C.-C., R. P. Lepping, and N. Gopalswamy (2006), Relationships among magnetic clouds, CMEs and geomagnetic storms, *Sol. Phys.*, *239*, 449–460.

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