Observations of an interplanetary slow shock associated with magnetic cloud boundary layer

P. B. Zuo, 1,2 F. S. Wei, 1 and X. S. Feng 1

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[1] The observations of the slow shocks associated with the interplanetary coronal mass ejections near 1 AU have seldom been reported in the past several decades. In this paper we report the identification of an interplanetary slow shock observed by Wind on September 18, 1997. This slow shock is found to be just the front boundary of a magnetic cloud boundary layer. A self-consistent method based on the entire R-H relations is introduced to determine the shock normal. It is found that the observations of the jump conditions across the shock are in good agreement with the R-H solutions. The intermediate Mach number \( M_f = U_n/(V_s \cos \theta_{nm}) \) is less than 1 on both sides of the shock. In the upstream region, the slow Mach number \( M_{s1} = U_{n1}/V_{s1} \) is 1.44 (above unity), and in the downstream region, the slow Mach number \( M_{s2} = U_{n2}/V_{s2} \) is 0.8 (below unity). Here \( V_s \) and \( V_A \) represent the slow magnetosonic speed and Alfvén speed respectively. In addition, the typical interior magnetic structure inside the shock layer is also analyzed using the 3s time resolution magnetic field data since the time for the spacecraft traversing the shock layer is much longer (about 17s). As a potential explanation to the formation of this kind of slow shock associated with magnetic clouds, this slow shock could be a signature of reconnection that probably occurs inside the magnetic cloud boundary layer.


1. Introduction

[2] There are two basic types of MHD shocks in the solar wind which are very important structures from the view of space plasma and heliospheric dynamics: fast shocks and slow shocks. The fast shocks are very common that have been frequently observed in interplanetary space. Considering their origins, there exist two classes of fast shocks: one is driven by the ejecta from solar eruptions and the other is associated with corotating streams [Burlaga, 1995]. The reports of slow shocks are relatively much rare. In the last several decades only a limited 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]. In theory the slow shocks can occur near the stream interfaces [Burlaga, 1974; Richter, 1991]. The slow shocks associated with the stream corotating stream have been observed by Ho et al. [1998] and Whang et al. [1996]. Ho et al. [1998] first discovered a slow shock pair in interplanetary space that were embedded inside a CIR. Slow shock might also form at coronal mass ejections in the corona, where the plasma beta is very low [Whang, 1987, 1988; Burlaga, 1995]. This type of slow shocks can easily transform to fast shocks between the sun and 1 AU, so that the slow shock might not be observed at 1 AU [Whang, 1987, 1988]. So far, to our knowledge no one has reported a slow shock associated with interplanetary coronal mass ejections at 1 AU. Fortunately, we strictly identify an interplanetary forward slow shock detected by Wind on September 18, 1997, and find that it was the front boundary of a magnetic cloud boundary layer. In this paper, we report the identification of such rarely observed slow shock. Meanwhile, a new method to determine the shock normal using Rankine-Hugoniot (R-H) relations is introduced, and the magnetic field structure of the slow shock layer is also analyzed using high-resolution magnetic field and plasma data from Wind.

2. Observations of a Slow Shock

2.1. Self-Consistent Method to Determine Shock Normal

[4] Several methods have been developed to determine the shock normal vector \( \mathbf{n} \). According to the coplanarity theorem, the magnetic field vectors \( \mathbf{B}_1 \) and \( \mathbf{B}_2 \) in the upstream and downstream region and \( \mathbf{n} \) are in a plane. The unit shock normal vector can therefore be obtained as follows [Colburn and Sonnet, 1966]:

\[
\mathbf{n} = \pm \frac{(\mathbf{B}_1 \times \mathbf{B}_2) \times (\mathbf{B}_2 - \mathbf{B}_1)}{|(\mathbf{B}_1 \times \mathbf{B}_2) \times (\mathbf{B}_2 - \mathbf{B}_1)|}
\]

(1)

The exact solutions of MHD shocks have been extensively studied by many researchers. Whang [1987] proposed that the solutions of R-H relations for MHD shocks may be expressed as function of three dimensionless preshock conditions: the shock intermediate Mach number \( M_I = U_n/\left(V_A \cos \theta_{Bn}\right) \), the shock angle \( \theta_{Bn} \), and the plasma \( \beta \) value (here \( U_n \) is normal component of the preshock bulk velocity in the frame of shock, \( V_A \) is the Alfvén speed, and \( \theta_{Bn} \) is the angle between the shock normal and the magnetic field). That is, for a given shock normal vector, the R-H relations can provide predictions of the downstream plasma parameters and magnetic fields using above three observational parameters in the upstream region (the calculating formulas can be found in Whang’s paper). If \( \theta \) and \( \phi \) represent the
2.2. Shock-Like Discontinuity

[5] The magnetic field data obtained from MFI and the proton and electron data obtained from SWE and 3DP are used for the slow shock search and identification. These instruments on board Wind were described by Lepping et al. [1995], Ogilvie et al. [1995], and Lin et al. [1995], respectively. Here the coordinate system used is the geocentric solar ecliptic (GSE) system. The requirements to identify slow shocks are relatively strict. Our criteria are as follows:

1. The mass density and temperature increase from the upstream region to the downstream region. On the contrary, the magnitude of magnetic field is expected to decrease;

2. The observations of all parameters meet the R-H relations;

3. The normal component of the bulk velocity in the shock frame must be larger than local slow magneto-acoustic speed and smaller than local normal Alfvén speed in the upstream region, and in the downstream region the corresponding normal velocity must be smaller than the local slow magnetoacoustic speed.

[6] Figure 1 gives 4 min of magnetic field and plasma data from Wind on September 18, 1997 to show the slow-shock-like discontinuity. The spacecraft was located at \( R = (191,3,18) R_E \) in the GSE coordinate system. Across the discontinuity the number density \( N \), the proton temperature \( T_p \), increased, the proton velocity \( V_p \) relative to the spacecraft also increased by \( \sim 9 \) Km/s, while the magnitude of magnetic field \( B \) decreased. These jump signatures are typical of a forward slow shock.

[7] The selection of time intervals representative of the upstream and downstream region of a shock for calculation is a long standing problem and somewhat arbitrary. In this study, since the time-resolution of the data is much higher (3s for MFI and 6s for SWE), we try to select the intervals of less than 3 min very close to the shock layer when the fluctuations are relatively weak. In addition, the intervals for the upstream and downstream region are confirmed through an optimization program, with the requirements that the mean error function \( \Delta \) calculated based on the selected intervals is the least. Table 1 shows the selected intervals and the averaged values of the magnetic filed vector \( \mathbf{B} \), the solar wind velocity vector \( \mathbf{V}_{sw} \), and the number density \( N \), the proton and electron temperature \( T_p \) and \( T_e \) on both sides of the shock layer. The jumps across the shock can be seen in detail in Table 1. The analysis below are on the basis of these observational data.

[8] On September 18 ~ 20, 1997, Wind observed a typical magnetic cloud, which can be found in the magnetic cloud list given by R. P. Lepping et al. (http://lepmfi.gsfc.nasa.gov/mfi/mag_cloud_pub1.html). This magnetic cloud is a multiple magnetic cloud which includes two isolated magnetic clouds with double rotations. The velocity of this ejecta is rather slow (the averaged value is \( \sim 340 \) Km/s). As defined by Wei et al. [2003a], a magnetic cloud boundary layer (MCBL) formed between the magnetic cloud and the ambient solar wind due to the interaction between them. In

![Figure 1](image_url)
U/C0 is the observed solar wind velocity in the L15107 region, the slow Mach number \( M_{s2} = \frac{U_{s2}}{V_{s2}} \) is below unity (0.80). Here \( V_{s} \) represents the slow magnetoacoustic speed. These flow conditions accord with the requirements of Criterion 3 (described in subsection 2.1).

To make a comparison with the self-consistent method (named method 1), we also use the coplanarity method (see Formula 1, named method 2) to determine the shock normal. The unit normal vector is \((0.30, 0.82)\) given by method 1 and \((-0.49, -0.30, 0.82)\) given by method 2 (in GSE). The angle between them is only 7°. Meanwhile, the minimum variance analysis (MVA) is applied to the entire magnetic cloud and shows that the direction of the MC’s minimum variance axis is \((-0.87, -0.39, -0.30)\). The angle between the shock normal vector given by method 1 and the MC’s axis is 73°. The observations and the predictions of the jump conditions based on the determined shock normal using method 1 (R-H solution 1) and method 2 (R-H solution 2) are displayed in Table 3. It can be found that the observations of jump conditions for all parameters are reasonably in good agreement with the predictions of the R-H relations using either method considering the error. Furthermore, R-H solution 1 are in better agreement with the observations than those by R-H solution 2 do on the whole. Evidently for the downstream shock angle, the observation and R-H solution 2 differ much. Thus the shock normal determined by the method 1 can be considered more accurate.

### 2.4. Interior Magnetic Structure of the Shock Layer

MHD shocks are not discontinuities in the strict sense but own some structures. Wind has traversed the shock layer for 17s (from 0255:07 UT to 0255:24 UT) with a speed of 205 Km/s. So the ramp thickness of the shock region, the slow Mach number \( M_{s2} = \frac{U_{s2}}{V_{s2}} \) is below unity (0.80). Here \( V_{s} \) represents the slow magnetoacoustic speed. These flow conditions accord with the requirements of Criterion 3 (described in subsection 2.1).

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### Table 2. Shock Normal, Shock Speed, the Angle Between the Field Direction and the Normal Vector, and the Flow Conditions on Both Sides of the Shock

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n ) (in GSE)</td>
<td>((-0.49, -0.30, 0.82))</td>
</tr>
<tr>
<td>( V_{sh} ), Km/s</td>
<td>205</td>
</tr>
<tr>
<td>( \theta_{sh1} )</td>
<td>54.2°</td>
</tr>
<tr>
<td>( \theta_{sh2} )</td>
<td>16.1°</td>
</tr>
<tr>
<td>( U_{s1} ), Km/s</td>
<td>22.0</td>
</tr>
<tr>
<td>( U_{s2} ), Km/s</td>
<td>15.6</td>
</tr>
<tr>
<td>( U_{n1}/V_{sh} )</td>
<td>0.97</td>
</tr>
<tr>
<td>( U_{n2}/V_{sh} )</td>
<td>0.80</td>
</tr>
<tr>
<td>( U_{s1}/V_{s1} )</td>
<td>1.44</td>
</tr>
<tr>
<td>( U_{s2}/V_{s2} )</td>
<td>0.80</td>
</tr>
</tbody>
</table>

### Table 3. Observations and the Predictions From the R-H Relations of the Jump Conditions Where R-H Solutions 1 and R-H Solutions 2 Are Based on the Shock Normal Determined by Methods 1 and 2, Respectively

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Observations</th>
<th>R-H Solutions 1</th>
<th>R-H Solutions 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_{2}/N_{1} )</td>
<td>1.41</td>
<td>1.28</td>
<td>1.23</td>
</tr>
<tr>
<td>( T_{2}/T_{1} )</td>
<td>1.06</td>
<td>1.21</td>
<td>1.15</td>
</tr>
<tr>
<td>( U_{s2}/U_{s1} )</td>
<td>0.71</td>
<td>0.78</td>
<td>0.82</td>
</tr>
<tr>
<td>( P_{2}/P_{1} )</td>
<td>1.50</td>
<td>1.55</td>
<td>1.42</td>
</tr>
<tr>
<td>( B_{2}/B_{1} )</td>
<td>0.63</td>
<td>0.61</td>
<td>0.73</td>
</tr>
<tr>
<td>( \theta_{sh1} )</td>
<td>54.2°</td>
<td>53.2°</td>
<td></td>
</tr>
<tr>
<td>( \theta_{sh2} )</td>
<td>16.1°</td>
<td>16.1°</td>
<td></td>
</tr>
<tr>
<td>( \theta_{pre} )</td>
<td>17.4°</td>
<td>34.8°</td>
<td></td>
</tr>
</tbody>
</table>
layer can be easily calculated to be 3485 Km about 73 times the ion inertial length \((c/\omega_p)\) which is much larger than that of the slow shocks in the distant geomagnetic tail. The reason for its larger thickness perhaps is that the observed slow shock is a relatively weak one with a slow Mach number of 1.44.

[12] Let \( \mathbf{n} \) denote the shock unit normal vector obtained from coplanarity theorem, and \( \mathbf{s} \) denote the unit vector normal to the coplanarity plane, which can be calculated from: \( \mathbf{s} = \pm \frac{\mathbf{B}}{B}, \) Then define: \( \mathbf{t} = \mathbf{s} \times \mathbf{n}. \) In this way we introduce a local discontinuity coordinate system whose three axes are along the direction of \( \mathbf{n}, \mathbf{t}, \mathbf{s} \) respectively. The unit direction vectors of three axes calculated using this coplanarity method are shown in Column 1 of Table 4. Now the interior magnetic structure is analyzed in this coordinate system using the 3s resolution magnetic field data. The results are as follows: the average and the variance of \( B_n \) (the component in the direction of \( \mathbf{s} \)) in the interior of shock layer are both only 0.04 nT. It indicates that the \( B_n \) inside the shock is nearly zero. Thus the magnetic field vector \( \mathbf{B} \) inside the shock layer is also nearly parallel to the coplanarity plane. The average of \( B_t \) (the component in the direction of \( \mathbf{t} \)) is \(-5.9 \) nT, and the variance is 0.26 nT which is also relatively small. It indicates that the \( B_t \) approximately keep unchanged. These characteristics of interior magnetic field are typical of MHD shocks.

[15] According to the divergence free condition and coplanarity theorem of the magnetic field, The variations in magnetic field components along the \( \mathbf{n} \) and the \( \mathbf{s} \) direction should both be zero. Thus along the \( \mathbf{t} \) direction the variation in magnetic field component should be a maximum. Above analysis reveals that the variance of \( B_t \) through the shock layer is less than that of \( B_n. \) Both of them are nearly zero, which accords with the theory. A minimum variance analysis on magnetic field (MVAB) was used here to newly search the direction of \( \mathbf{n}, \mathbf{t}, \mathbf{s} \) for comparison with the coplanarity method. From above discussions, the \( \mathbf{t} \) axis should along the direction corresponding to the maximum eigenvalue \( \lambda_1, \) \( \mathbf{n} \) axis should along the direction corresponding to the intermediate eigenvalue \( \lambda_2, \) and the \( \mathbf{s} \) axis should be along the direction corresponding to the minimum eigenvalue \( \lambda_3. \) The results given by the MVAB technique are shown in Column 2 of Table 4. The acquired directions of three axes are in good agreement with those calculated from the above coplanarity method since the angle between the directions given by two methods is very small for each axis (See Table 4).

### 3. Conclusions and Discussions

[14] The uncertainty to analyze the shocks is, to some extent, related to the time resolution of the data provided. In some previous studies, the discussed preshock and postshock parameters are the averaged data over a time interval of from several minutes even to one hour as a result of relatively low resolution plasma data. However, the flow conditions vary substantially on both sides of the shock over such a longer interval. Furthermore, both shock induced fluctuations and constantly arising solar wind fluctuations must be taken into consideration. Thus it becomes difficult to justify that the averaged conditions can represent the preshock and postshock conditions in this circumstance. We had tried to select the intervals of 10 min representative of both sides of the shock as many people usually do, but found that the R-H relations can’t be satisfied on this condition. Considering this point, in this paper we use data with the time-resolution of 3s for MFI and 3DP, and 6s for SWE, and selected intervals of \( \sim \)30s for the upstream and downstream regions, which are very close to the shock layer. In this way we can obtain rather more accurate preshock and postshock conditions immediately outside the shock layer used in the R-H analysis.

[15] In this study, a slow shock is identified strictly using the high-resolution data. With our analysis, the observations of this slow shock satisfy all the three criteria described in Subsection 2.1, which can fully characterize slow shocks. Most importantly, this slow shock is associated with a magnetic cloud, which has seldom been observed. It’s known that slow shocks may play an important role in magnetic reconnection in space plasma in theory [Petschek, 1964]. Wei et al. [2003a] have proposed that the MCBLs perhaps form due to the reconnection between the magnetic cloud body and ambient solar wind in terms of some simulation results. Some evidences in observation and simulation about the reconnection between the solar wind and magnetic cloud have also been found by Zhong et al. [2005] and Schmidt and Cargill [2003]. As shown in Figure 2, some features, which represent the basic state of the magnetic reconnection region, such as the magnetic field intensity drop associated with the abrupt change of the field direction, and the heating of the proton, can be found inside the MCBL. As a potential explanation to the formation of this kind of slow shock associated with magnetic clouds, we speculate that this slow shock might be another signature of the reconnection that can probably occur inside the MCBL. Of course, more direct evidences must be found to testify the occurrence of the reconnection process inside the MCBL. It is a very intriguing topic for future study to find more evidences and make clear the relationship between the slow shocks and such reconnection process.

<table>
<thead>
<tr>
<th>Axes</th>
<th>Coplanarity Method</th>
<th>MVAB</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n )</td>
<td>((-0.44, -0.38, 0.81))</td>
<td>((-0.49, -0.37, 0.79))</td>
<td>3.4°</td>
</tr>
<tr>
<td>( s )</td>
<td>((0.43, -0.88, -0.17))</td>
<td>((0.44, -0.89, -0.14))</td>
<td>1.6°</td>
</tr>
<tr>
<td>( t )</td>
<td>((-0.79, -0.28, -0.55))</td>
<td>((-0.75, -0.27, -0.60))</td>
<td>3.6°</td>
</tr>
</tbody>
</table>

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### References


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