The evolution of shocks near the surface of Sun during the epoch of Halloween 2003

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Abstract

We use a one-dimensional, time-dependent adaptive grid MHD code to study the evolution of shocks (both slow and fast shocks) from the surface of the Sun through the heliosphere. In order to achieve the goal, we track a specific solar event’s plasma and magnetic field output as it propagates into interplanetary space with a possible geoeffective consequence. We have chosen the famous event of the October/November (”Halloween 2003”) epoch which produced two of the largest geomagnetic storms during solar cycle 23, followed by the arrivals of the shocks at Earth. These two geomagnetic storms are associated with two of these flares (X17/4B and X10/2B). Accordingly, four separate pressure pulses, at the appropriate times and with different strengths and duration, determined via a trial and error procedure, are introduced on the Sun to mimic the four flares. The results show that the simulated solar wind velocity temporal profiles successfully matched the observations at L1. The propagation speed of shock waves near the Sun also matched with the CME observations of SOHO/LASCO. The major objective, to demonstrate the detailed nature of interacting shocks and some of their products after origination from closely spaced solar events, is achieved. The evolution of both slow and fast shocks is also discussed in detail.
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1. Introduction

Since Gold (1955) suggested the existence of shock waves in the solar wind, propagating fast forward shocks have been the most frequently observed and analyzed type of shock wave. Unlike fast mode shock waves, only a few interplanetary slow mode shocks have been identified at
heliocentric distances greater than 0.3 AU (Chao and Olbert, 1970; Burlaga and Chao, 1971; Richter et al., 1985; Whang et al., 1996). Whang (1987) suggested that the decrease in the Alfvén speed at increasing heliocentric distance causes the normal Alfvén Mach number of a forward slow shock (FSS) to become greater than 1, and the shock should eventually evolve from a slow shock into a fast shock. However, two previous studies (Chao et al., 1987; Wu et al., 1996a) employed two ideal finite-difference MHD simulation codes to simulate a slow forward shock’s propagating in a nonuniform solar wind. The simulation demonstrated that the speed of the slow shock decreases and that the slow shock does not evolve into a fast shock in a special situation that involves propagation into a positive density gradient. Wu et al. (2004a) used a one-dimensional, time-dependent adaptive grid MHD code (Panitchob et al., 1987) to study the interaction between fast and slow shocks in the solar wind between 0.1 and 1 AU. They found that a FSS can be destroyed by a forward fast shock (FFS) that overtakes it from behind and the strength of a FSS is decreased by following an FSS. During the transition of a fast shock’s overtaking a slow shock from behind, the slow shock might disappear temporarily (Wu et al., 2005a). The study of Wu et al. (2005a) also shows that during the process of the merging of two slow shocks, a slow shock-like structure is formed first; later, the slow shock-like structure evolves into an intermediate shock-like structure. This intermediate shock-like structure then evolves into an intermediate wave (IW) and a slow shock-like structure.

In this paper, we use the same one-dimension, time-dependent, adaptive-grid, MHD model with a representative solar wind structure which was used by the previous workers (Wu et al., 1996a,b, 2004a, 2005a) to study the evolution and interaction of both slow and fast shocks from the surface of Sun through the heliosphere.

In order to achieve the goal, we would like to track a specific solar event’s plasma and magnetic field output as it propagates into interplanetary space with a possible geoeffective consequence. This latter objective is especially important for forecasting purposes when staccato solar events take place. The October/November (“Halloween 2003”) epoch provided an exceptional case in point. Two of the largest geomagnetic storms occurred during this period. The near real time effort (Dryer et al., 2004) to predict the shock times of arrival at L1 presents an example of this operationally imperative objective. An extensive overview of the Halloween solar-heliospheric events is provided by Veselovsky et al. (2004).

We will describe the mathematical methods in Section 2, numerical MHD simulation results in Section 3, and a discussion of these results in Section 4.

2. Mathematical methods

The numerical model used in this analysis is an extension of the two-step Lax–Wendroff finite difference method. The details of the computation procedures are given by Panitchob (1987) and Panitchob et al. (1987); therefore they will not be repeated here. The procedure of the shock strength Mach number calculation method is based strictly on steady-state mass flux through the shock, regardless of its type (fast, slow, intermediate, etc.). We also used a straightforward method of calculating the average shock Mach number between two radial positions as the shock propagated from one position at time, \( t_1 \) (say) to a second position at \( t_2 \). We call this latter procedure the wave transit method (WTM). The detailed computational procedure for WTM is given by Wu et al. (1996a,b).

3. Observations

Fig. 1 shows ACE/SWEPAM/SWICS/MAG solar wind plasma and magnetic field data between October 28 and November 1, 2003. The bottom panel shows the solar wind velocity profile. Three shocks (marked by the vertical dotted lines) occurred on October 28, 29, and 30, 2003. A discontinuity, marked DD (to be discussed later), is noted by a vertical solid line at a smaller velocity increase from 600 to 650 km/s between two shocks observed on October 28 and 29 (DOY 301 and 302, respectively). The proton density, in the second panel from the bottom, is not available (Skoug et al., 2004) in a reliable form during the period from 0600 UT, October 29, to 0400 UT, October 30, 2003. The third panel for the temperature is notable for the flare-like value of \( T = 10^7 \) (K) reached immediately after the second shock’s arrival. The next two panels, moving upward in Fig. 1, show the total IMF magnitude and its three components: \( B_x, B_y, \) and \( B_z \) in the GSE (geocentric solar ecliptic) coordinate system. The next two panels near the top give the three velocity components \( V_x, V_y, \) and
The top panel, which shows the \( D_{st} \) response of the magnetospheric ring current, shows the two observed sudden storm commencements (SSCs), marked by the vertical dashed lines. The \( D_{st} \) dropped to \(-363\) nT, 20 h after the second shock observed by ACE (Advanced Composition Explorer) spacecraft; and to \(-401\) nT, 4 h after the third shock observed by ACE. A summary of the four chosen flares during the period from October 25 to October 29, 2003, is given in Table 1.

**Table 1**

Characteristics of the four flares

<table>
<thead>
<tr>
<th>Occurrence of flare</th>
<th>Class</th>
<th>Location</th>
<th>( \Delta t ) (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0552 UT, 2003-10-25</td>
<td>LDE M1.7/SF</td>
<td>N00W15</td>
<td>0</td>
</tr>
<tr>
<td>0617 UT, 2003-10-26</td>
<td>LDE X1.2/3N</td>
<td>S18E33</td>
<td>24.42</td>
</tr>
<tr>
<td>1102 UT, 2003-10-28</td>
<td>X17/4B</td>
<td>S15E08</td>
<td>77.0</td>
</tr>
<tr>
<td>2041 UT, 2003-10-29</td>
<td>X10/2B</td>
<td>S15W02</td>
<td>110.67</td>
</tr>
</tbody>
</table>

\( ^a \)The flare time is listed as the radio metric Type II start time that is close to the maximum of the soft X-ray emission in 1-8A.
4. Simulation results

In the present study, the simulation domain is taken to be between 1 solar radius \((R_\odot)\), (the surface of the Sun) and \(400R_\odot\). We first performed a parametric study using the adaptive grid 1.5D MHD code to obtain temporal solar wind velocity profiles at 1 AU by using only velocity, temperature, and density pulses. We did not consider magnetic flux emergence in these 1.5D exercises. Details of choices for pressure pulses are described in the study of Wu et al. (2005b). We consider the final choices (Fig. 2) to be physically reasonable but make no claim that these combinations are unique. Four pressure pulses were chosen. Fig. 2 shows the evolution of perturbation variables at the lower boundary, the surface of the Sun. We classify the perturbations with various combinations of physical parameters: \((\rho'/\rho_0, T'/T_0)\), \(T_0\) and \(\rho_0\) represent the “steady state” of the solar wind. \(T_0\) and \(\rho_0\) represent the variations of temperature and density, respectively, that are assumed, as just discussed, to mimic each flare. The temporal variation of the perturbation is a “near square wave” with a one-hour rise and decay separated by various constant magnitude durations at \(1R_\odot\). Four pressure pulses were chosen after the trial and error procedure described above. The sequential pressure pulses were initiated at time, \(t = 0, 24.42, 77,\) and 110.67 h that correspond to the times (in DOY, 2003) 298.24, 299.26, 301.45, and 302.86, respectively. The launch time of each pressure pulse, then, is identical with the flare onset time on the Sun.

Fig. 2 shows the temporal evolution of the four pressure pulses (Wu et al., 2005b). For example, the largest pressure pulse (third one) represents the largest, X17/4B, flare. Pulse 1, then, will propagate into the steady-state solar wind plasma and magnetic field shown in Fig. 3 from the Sun to \(400R_\odot\). The vertical line indicates the location of 1 AU.

Fig. 4 shows, in higher resolution, the solar wind speed monitored at ACE in both the simulation (solid line) and observations (dotted line) (Wu et al., 2005b). The arrival times of the three simulated shocks and the discontinuity (DD) match quite well with ACE’s observations. In addition, the simulated plasma speed profiles behind the three shocks are also in good agreement with the observations. The reader is reminded that the simulated shock arrival times were already matched to the actual arrival times via the trial and error procedure discussed earlier. The DD comparison, however, is considered to be an important new result. Also, the good agreement of the velocity profiles suggests that this pressure pulse procedure, albeit non-unique, is physically realistic as a flare proxy. In fact, in a numerical test of various physical mechanisms responsible for initiation and acceleration of CMEs (coronal mass ejections), Wu et al. (2004b) found that the fastest, flare-associated CMEs were initiated by introducing heating (i.e., a sufficiently large pressure pulse) into a flux rope, thereby simulating an active region flux-rope accompanied by a flare to launch a CME.

5. Evolution of shocks near the Sun

In order to understand the detailed evolution of shock evolution near the surface of Sun, we will concentrate on the shocks’ formation and interactions near the Sun. We will direct our attention to the development of various shocks (and other discontinuities) associated with Pulse 1 that we use.
to mimic the X17/4B flare on 27 October 2003 as mentioned above. Figs. 5 and 6 show the evolution of the shock near the Sun (within $R_\odot$). The vertical solid lines indicate the location of FSS or IW structure, and the vertical dotted lines indicate (Fig. 6) the location of a FFS. Fig. 5(a) shows the steady state condition between the surface of Sun and $20R_\odot$. Fig. 5(b) clearly shows that a FSS, indicated by a jump in $V_r, N_p,$ and $T$ but a $B$ decrease, was formed (near $6R_\odot$) two hours after the first pressure pulse was launched. However, the slow shock survived for only a couple of hours. Then it became an IW structure since the sign of $B_f$ is opposite for the up- and down-stream condition (see Figs. 5(d) and 6(a)). While FSS was evolving into an IW, a FFS was formed near $18R_\odot$ in the front of IW (see Fig. 6(a)). The IW was not stable and evolved into a FSS again after the signs of the rotating $B_\theta$ are the same in both up- and down-stream. However, we added a question mark behind the FSS on Fig. 6(b)–(d) because the change in velocity between upstream and downstream is very small (there is almost no change in Fig. 6(d)). We mark a ‘FSS?’ in Fig. 6(b)–(d) because the Mach no. of FSS is greater than 1. The definition
Fig. 5. Solar wind plasma and magnetic field data for time $t = 0, 2, 3$ and $4$ h, respectively. The vertical line indicates the forward slow shock or an intermediate wave.
of the various Mach number are $M_f = V^* / C_f$, $M_{\text{slow}} = V^* / C_{\text{slow}}$, $M_A = V^* / C_A$. In these equations, $M_f$, $M_{\text{slow}}$ and $M_A$ are the fast Mach number, slow Mach number and Alfvén Mach number; $C_A$, $C_f$ and $C_{\text{slow}}$ are the speeds of Alfvén waves, fast waves and slow mode waves; $V^*$ is the bulk
velocities’ frame of reference, where $V^* = V_S - V$ ($V$ is the solar wind speed, $V_S$ is the propagation speed of shock waves).

In this study, four pressure pulses were launched on the surface of Sun at different times (Fig. 2) in order to mimic the flares observed. The evolution of

Fig. 7. Solar wind plasma and magnetic field data for time $t = 26, 27, 29$ and $32$ h, respectively. The vertical lines indicate the intermediate wave, fast forward shock and slow shock wave, respectively.
the simulated shocks that were created by different pressure pulses are similar: (1) a FSS was always generated earlier than the FFS; (2) the FSS evolved into an IW while the FFS is formed; or (3) the FSS became a slow shock-like structure after the FFS is formed. For example, Fig. 7 shows the evolution of shocks generated by the second pressure pulse. (The second pressure pulse was launched 24 h (see Fig. 2) after the first pressure pulse was launched.) A FSS was generated near 5\(R_{\odot}/C_{12}\) two hours after the pressure pulse was launched (see Fig. 7(a) at \(t = 26\) h). Three hours later, the FSS evolved into an IW, and a FFS was formed in front of the IW (see Fig. 7(c)–(d)).

We use WTM (Wu et al., 1996a,b) to calculate the propagation speed of FFSs that were produced by the four pressure pulses. The brief summary is listed in Table 2. The averaged propagation speeds of the shocks, produced by the pressure pulses 1, 2, 3, and 4, were 728, 1028, 2125, 1915 km/s between the location of their starting formation and 85\(R_{\odot}\).

6. Discussion

The current results clearly show that a FSS will be formed after a pressure pulse is added on the Sun. However, this FSS is not stable while the FFS is forming. The FSS will evolve into an IW (intermediate wave) while a FFS is forming in front of it. However, this FSS evolves back to a FSS again or into a slow shock-like structure. This behavior is consistent with the Helios observations (Richter, 1987) where transient fast shocks were more frequently followed within a few hours by slow shock-type discontinuities rather than by fast reverse shocks. This feature is also confirmed previously by Wu et al. (2005a) by using the same MHD simulation model except that they started their calculation at the lower boundary of 28\(R_{\odot}\) instead of the surface of the Sun. In addition, Wu et al. (2004a) also showed that a FSS might evolve into an IW while the FSS was being overtaken by a FFS from behind. In this study, the FSS became an IW while a FFS was forming in front of the FSS. Wu et al. (1996b, 2004a, 2005a) showed (in intensive parametric studies) that a positive, square-wave perturbation (pressure pulse), for example, will generate both fast and slow shocks. In the present, more complicated but realistic simulation, we added four perturbations to mimic the effect due to flares at the Sun, but only three fast shocks were observed at L1, and no slow shock was observed. The issue of why only three shocks were observed was discussed in detail by Wu et al. (2005b) (because the shocks generated by the first and second pulses were merged into one shock). Therefore, we are not going to repeat it here. As mentioned above, a positive, square-wave pressure pulse will generate slow shocks. However, to our knowledge, ACE experimenters have not reported studies of such kind of finding. Therefore, it is important, in our opinion, to study the kinds of shocks at L1 as well as to understand the evolution of shocks near the sun.

Our previous study (Wu et al., 2005b) compared the speed of the shock which was produced by the third flare (X17/4B, 1102 UT, October 28, 2003) between observation and simulation. The simulation results matched the observation. In this study, Table 2 shows the detailed characteristics of four fast shocks. The speed calculated from the simulation is close to the observation of the measured CME speeds. Their correspondence, as noted in the footnote of Table 2, suggests that the catalogued CME speeds might actually be those for their shocks. It also shows clearly that the delay time to form a shock is shorter when an intense pressure pulse is applied as compared to a shorter timed pressure pulse. Such a more intense pressure pulse-generated shock would naturally be expected to have a higher propagation Mach number.

### Table 2
Forming time, forming location, and shock speed propagation of forward fast shock generated by pressure pulse

<table>
<thead>
<tr>
<th>Pressure pulse</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forming time (hours)</td>
<td>4.45</td>
<td>4.04</td>
<td>0.83</td>
<td>1.46</td>
</tr>
<tr>
<td>Forming location ((R_{\odot}))</td>
<td>15.3</td>
<td>13.9</td>
<td>5.8</td>
<td>5.1</td>
</tr>
<tr>
<td>Shock speed (km/s)</td>
<td>728</td>
<td>1028</td>
<td>2125</td>
<td>1915</td>
</tr>
<tr>
<td>LASCO shock speed (km/s)</td>
<td>685</td>
<td>1371</td>
<td>2459</td>
<td>2029</td>
</tr>
<tr>
<td>Mach no.</td>
<td>2.31</td>
<td>2.66</td>
<td>9.91</td>
<td>7.21</td>
</tr>
</tbody>
</table>

*a* The time delay of a pressure pulse for producing a fast shock near the Sun.

*b* The averaged propagation speed of forward fast shock near the Sun (between the forming location and 85\(R_{\odot}\)).

*c* We might assume that the closeness of the shock speed to the CME speed (catalogued from SOHO/LASCO observations and adapted from http://cdaw.gsfc.nasa.gov/CME_list/ produced by Drs. Seiji Yashiro and Nat Gopalswamy) implies that the two might be identical.

*d* The Mach numbers are computed via WTM (Wu et al., 1996a,b).
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