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In situ local shock speed and transit shock speed

S. Watari¹ and T. Detman²

¹ Communications Research Laboratory, 4-2-1 Nukuikita, Koganei, Tokyo 184-8795, Japan
² NOAA/Space Environment Center, 325 Broadway, Colorado, 80303 USA

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Abstract. A useful index for estimating the transit speeds was derived by analyzing interplanetary shock observations. This index is the ratio of the in situ local shock speed and the transit speed; it is 0.6–0.9 for most observed shocks. The local shock speed and the transit speed calculated for the results of the magnetohydrodynamic simulation show good agreement with the observations. The relation expressed by the index is well explained by a simplified propagation model assuming a blast wave. For several shocks the ratio is approximately 1.2, implying that these shocks accelerated during propagation in slow-speed solar wind. This ratio is similar to that for the background solar wind acceleration.

Keywords. Interplanetary physics (Flare and stream dynamics; Interplanetary shocks; Solar wind plasma)

1 Introduction

Interplanetary shock propagation has been studied. Dryer (1974 and references therein) reviewed the observational and theoretical approaches to explaining those shock waves. Pinter (1982 and references therein) reviewed the general properties of those shocks based on observations.

The Mariner 2 spacecraft recorded an interplanetary shock on 7 October 1962 (Sonnet et al., 1964), the first direct observation of an interplanetary shock. The sudden commencement (SC) of a geomagnetic storm was recorded in association with this shock. Gosling et al. (1968) noted that the speed of the shocks observed by the twin Vela 3 satellites was significantly less than the transit speed of the shock from the Sun to Earth. Hundhausen (1970) calculated the transit speed by using the timing between the eruptive flare and the SC for the shocks between 1962 and 1967. Comparing the in situ speed with the transit speed indicated that most shocks decelerated during transit.

Chao and Lepping (1974) compared the shocks with the in situ speed for 22 events associated with eruptive flares. Their analysis was based on observations by the eight spacecraft (Explorer 33, 34, 35, 41, and 43; Pioneer 7 and 8; and Ogo 5). The in situ speeds were lower than the mean transit speeds, suggesting that shocks decelerated.

Mihalov et al. (1987) compared the transit speed of shocks from the Sun to the Pioneer Venus Orbiter (PVO) spacecraft with the transit speed from the Sun to Earth. The transit speeds to Earth tended to be less than those to Venus, indicating deceleration of the shock during propagation. The faster shocks tended to have greater deceleration.

Cane (1983) deduced the velocity profiles of shocks from interplanetary (IP) type II observations by the ISEE 3 spacecraft. The shocks accelerated near the Sun, then decelerated.

Volkmer and Neubauer (1985) analyzed 178 fast magnetohydrodynamic (MHD) shocks observed by the HELIOS-1 and -2 spacecraft. They found that speeds in the solar wind frame are roughly proportional to $R^{0.5}$, where $R$ is the distance in astronomical units (AUs).

Smart and Shea (1985) constructed a simplified shock propagation model based on Volkmer and Neubauer’s (1985) finding. They assumed that a shock is initially driven near the Sun, then changes into a blast wave as it propagates through the interplanetary medium. Pinter and Dryer (1990) extended their study by considering solar radio emission in association with the eruptive flares to determine the initial driven condition of the shock. Their extended model showed good agreement for 39 shock events between 1972 and 1982.

Cliver et al. (1990) examined the relationship between transit shock speed $V_t$ and the corresponding maximum solar wind speed at Earth, $V_{max}$. They obtained $V_{max} = 0.775 \cdot V_t - 40$ km/s.

Vlasov (1988) analyzed the interplanetary scintillation observations and noted that the shock speeds,
including the background solar wind, are proportional to \( R^{-\gamma} \), where \( 0.25 \leq \gamma \leq 1 \). Beyond 2 AU, Dryer et al. (1978) noted that the transit shock speeds are proportional to \( R^{-0.08} \).

Theoretical approaches to shock propagation have been intensively investigated since Parker’s pioneering work (Parker, 1963). Reviews of this work include Dryer (1974, 1994), Hundhausen (1985, 1988), Pizzo (1985), and Dryer et al. (1988).

Smith and Dryer (1990) used \( 2\frac{1}{2} \)-dimensional magnetohydrodynamic (\( 2\frac{1}{2} \)-D MHD) time-dependent simulation for a parametric study of interplanetary shock propagation. They summarized the expected properties of the shocks at 1 AU for several levels of energy input near the Sun.

We have statistically analyzed the in situ shock observations and found a useful index for estimating the transit speed. We compared our results with those of Smith and Dryer’s (1990) MHD simulation and with those of a simple model assuming a blast wave. We identified several shocks that appear to have accelerated even in the slow-speed solar wind.

### 2 Statistical analysis of local and transit shock speeds

#### 2.1 Observed deceleration at 1 AU

Cane et al. (1987) listed the relation among interplanetary shocks, IP type II radio bursts, and coronal mass ejections (CMEs). We used their result to determine the relation between transit and in situ local speed so that we could estimate the shock deceleration at 1 AU.

Cliver et al. (1990) found that \( V_{\text{max}} \), the peak speed of a transit disturbance, equals 0.775\( V_t \) – 40 km/s for average shock speed \( V_t \). Their result is based on Cane’s (1985) list, which describes the relation between flares and IP type II shocks. Cane et al. (1987) re-examined Cane’s (1985) list by using the coronagraph images Table 1. Sixteen interplanetary shocks selected from Cane et al. (1987)

<table>
<thead>
<tr>
<th>Date</th>
<th>Time (UT)</th>
<th>SC</th>
<th>( V ) (km/s)</th>
<th>( V_s ) (km/s)</th>
<th>( V_b ) (km/s)</th>
<th>( V_s/V_b )</th>
<th>( (V_s - V_b)/(V_h - V_b) )</th>
</tr>
</thead>
<tbody>
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<td>0405</td>
<td>0155</td>
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<td>622</td>
<td>408</td>
<td>0.79</td>
</tr>
<tr>
<td>1979.08.18</td>
<td>1639</td>
<td>0820</td>
<td>0625</td>
<td>1030</td>
<td>717</td>
<td>489</td>
<td>0.70</td>
</tr>
<tr>
<td>1979.08.26</td>
<td>2016</td>
<td>0829</td>
<td>0459</td>
<td>700</td>
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<td>0.85</td>
</tr>
<tr>
<td>1980.04.04</td>
<td>1541</td>
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<td>950</td>
<td>675</td>
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<td>0.71</td>
</tr>
<tr>
<td>1981.04.01</td>
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<td>0403</td>
<td>0347</td>
<td>830</td>
<td>517</td>
<td>472</td>
<td>0.62</td>
</tr>
<tr>
<td>1981.05.08</td>
<td>2335</td>
<td>0510</td>
<td>2208</td>
<td>870</td>
<td>531</td>
<td>356</td>
<td>0.61</td>
</tr>
<tr>
<td>1981.05.13</td>
<td>0415</td>
<td>0514</td>
<td>1856</td>
<td>1070</td>
<td>600</td>
<td>438</td>
<td>0.56</td>
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<tr>
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<td>0900</td>
<td>0516</td>
<td>0532</td>
<td>930</td>
<td>746</td>
<td>522</td>
<td>0.80</td>
</tr>
<tr>
<td>1981.05.16</td>
<td>1042</td>
<td>0517</td>
<td>2302</td>
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<td>799</td>
<td>430</td>
<td>0.75</td>
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<tr>
<td>1981.08.07</td>
<td>2003</td>
<td>0810</td>
<td>0434</td>
<td>730</td>
<td>499</td>
<td>364</td>
<td>0.66</td>
</tr>
<tr>
<td>1981.11.09</td>
<td>1350</td>
<td>1111</td>
<td>1238</td>
<td>870</td>
<td>650</td>
<td>364</td>
<td>0.75</td>
</tr>
<tr>
<td>1981.11.22</td>
<td>0759</td>
<td>1125</td>
<td>0229</td>
<td>620</td>
<td>450</td>
<td>331</td>
<td>0.73</td>
</tr>
<tr>
<td>1981.12.09</td>
<td>2051</td>
<td>1212</td>
<td>0144</td>
<td>760</td>
<td>455</td>
<td>361</td>
<td>0.60</td>
</tr>
<tr>
<td>1981.12.27</td>
<td>0327</td>
<td>1229</td>
<td>0455</td>
<td>830</td>
<td>545</td>
<td>412</td>
<td>0.66</td>
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<td>0201</td>
<td>1100</td>
<td>1170</td>
<td>595</td>
<td>472</td>
<td>0.51</td>
</tr>
<tr>
<td>1982.09.04</td>
<td>0524</td>
<td>0905</td>
<td>2250</td>
<td>940</td>
<td>807</td>
<td>487</td>
<td>0.86</td>
</tr>
</tbody>
</table>

Average \( \pm SD \) | 889 ± 144 | 613 ± 110 | 422 ± 56 | 0.70 ± 0.10 | 0.42 ± 0.16 |

Fig. 1. Scatter plots of \( V_s \) versus \( V_t \) (upper panel) and \( (V_s - V_b)/(V_h - V_b) \) (lower panel)
taken by the Solwind spacecraft in association with IP type II shocks. Then they made the IP type II event list associated with CMEs. Cliver et al. (1990) used maximum bulk flow velocity $V_{max}$ instead of local shock speed $V_s$. They did not consider the background solar speed $V_b$ in their analysis.

We checked the availability of solar wind data for the shocks in Canes’s (1987) list and selected sixteen shocks. We added $V_b$, $V_s$, $V_b/V_s$, and $(V_b - V_s)/(V_b - V_t)$ by using the OMNI data. Table 1 shows the sixteen shocks.

The average ratio of $V_b/V_s$ is 0.70 ± 0.10. This ratio is 0.42 ± 0.16 after subtracting background solar wind speed $V_b$ from both $V_s$ and $V_b$. Here we consider the slow solar wind preceding the shocks as the background solar wind speed $V_b$. The expected ratio $(V_b - V_s)/(V_t - V_b)$ for the blast wave is 0.5. The scatter plots of $V_b$ versus $V_s$ and $(V_b - V_s)/(V_t - V_b)$ are shown in Fig. 1.

### 2.2 Distance dependence

To analyze the distance dependence of the ratio $V_b/V_s$, we selected 44 interplanetary shocks observed in association with CMEs and where the ratio $V_b/V_s$ is less than one. Table 2 shows these shocks. These shocks were observed by the HELIOS-1 spacecraft (Sheeley et al., 1985). The HELIOS-1 spacecraft observed the solar wind at various solar distances.
Figure 2 shows the distance dependence of the ratios $V_s/V_t$ and $(V_s - V_b)/(V_t - V_b)$. The distance dependence of both is weak. This suggests that the shock speeds were decelerated according to the same radial dependence in this range.

The scatter of the data increases after subtracting the background solar wind speed. The average ratios in the ranges 0.25–0.50, 0.50–0.75, and 0.75–1.00 AU are summarized in Table 3.

### 2.3 Comparison with MHD Simulation

Smith and Dryer (1990) calculated the shock propagation from the Sun to Earth under several initial conditions by using MHD simulation. They put shock pulses at 1.8 Rs (solar radius) into their computational domain. The steady-state background solar wind was assumed. It was taken to be uniform in azimuth in ecliptic plane, and the interplanetary magnetic field had the form of an Archimedian spiral. The ratios based on their result (Fig. 7 in Smith and Dryer, 1990) are summarized in Table 4. $V_i$ is initial shock speed. The ratios between the average transit speed and the local speed vary between 0.70 and 0.83. Those ratios are between 0.47 and 0.80 after the background solar wind speed was subtracted. The effect of the background solar wind becomes weak for strong shocks with a long driving time.

Smith et al. (1995) calculated the $V_s/V_t$ for the flux rope propagation obtained by MHD simulation to be $0.7 \sim 0.9$, which is in line with our result.

### 3 A Simplified Shock Propagation Model

We examined the observational results using the simplified model of Smart and Shea (1985).

We assumed the following radial distance dependence of shock speed $V_S$, where $R$ is the radial distance ($R_1 < R_2$), and that background solar wind speed $V_0$ is constant.

$$ V_S = V_{50} + V_0 $$

$$ V_S = V_{50}(R/R_1)^{-\alpha} + V_0 \quad \text{for } R_1 \leq R \leq R_2 $$

Transit time $T_{R2}$ to $R_2$ is given by

$$ T_{R2} \approx \frac{\alpha}{1 + \alpha} \frac{R_1}{V_{R1}} - \frac{\alpha}{1 + \alpha}(1 + 2\alpha) \frac{V_0 R_1}{V_{R1}^2} $$

$$ + \frac{1}{1 + \alpha} \frac{R_2}{V_{R2}} - \frac{\alpha}{1 + \alpha}(1 + 2\alpha) \frac{V_0 R_2}{V_{R2}^2} $$

### Table 3. Distance dependence of ratios between transit and local shock speeds

<table>
<thead>
<tr>
<th>Distance (AU)</th>
<th>Number of data</th>
<th>$V_s/V_t$</th>
<th>$(V_s - V_b)/(V_t - V_b)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25–0.50</td>
<td>4</td>
<td>0.80 ± 0.09</td>
<td>0.56 ± 0.14</td>
</tr>
<tr>
<td>0.50–0.75</td>
<td>17</td>
<td>0.82 ± 0.15</td>
<td>0.65 ± 0.20</td>
</tr>
<tr>
<td>0.75–1.00</td>
<td>22</td>
<td>0.81 ± 0.08</td>
<td>0.58 ± 0.15</td>
</tr>
</tbody>
</table>

### Table 4. Interplanetary shock speeds deduced from MHD simulation by Smith and Dryer (1990)

<table>
<thead>
<tr>
<th>$V_i$ (km/s)</th>
<th>$\tau$ (h)</th>
<th>$V_t$ (km/s)</th>
<th>$V_s$ (km/s)</th>
<th>$V_b$ (km/s)</th>
<th>$V_s/V_t$</th>
<th>$(V_s - V_b)/(V_t - V_b)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>0.5</td>
<td>700</td>
<td>520</td>
<td>360</td>
<td>0.74</td>
<td>0.47</td>
</tr>
<tr>
<td>1000</td>
<td>2</td>
<td>800</td>
<td>610</td>
<td>360</td>
<td>0.76</td>
<td>0.57</td>
</tr>
<tr>
<td>2000</td>
<td>0.5</td>
<td>1360</td>
<td>950</td>
<td>360</td>
<td>0.70</td>
<td>0.59</td>
</tr>
<tr>
<td>2000</td>
<td>2</td>
<td>1700</td>
<td>1400</td>
<td>360</td>
<td>0.82</td>
<td>0.78</td>
</tr>
<tr>
<td>3000</td>
<td>0.5</td>
<td>2100</td>
<td>1500</td>
<td>360</td>
<td>0.71</td>
<td>0.66</td>
</tr>
<tr>
<td>3000</td>
<td>2</td>
<td>2600</td>
<td>2150</td>
<td>360</td>
<td>0.83</td>
<td>0.80</td>
</tr>
</tbody>
</table>
where
\[ V_{R1} = V_{20} + V_0 \quad \text{at } R_1 \]
\[ V_{R2} = V_{20} \left( \frac{R_2}{R_1} \right)^{-2} + V_0 \quad \text{at } R_2 \]  
(3)

The ratio between local shock speed \( V_{R2} \) and transit speed \( V_{R2} \) is
\[ \frac{V_{R2}}{V_{R2}} = \frac{V_{R2}}{V_{R2}} \sum \left[ 1 + \alpha \left( \frac{V_0}{V_{R2}} \right) \right] \left( \frac{V_0}{V_{R2}} \right) \left( \frac{V_0}{V_{R2}} \right) \left( \frac{V_0}{V_{R2}} \right) \left( \frac{V_0}{V_{R2}} \right) \]  
(4)

If \( \alpha = 0.5 \) (Volkmer and Neubauer, 1985), then
\[ \frac{V_{R2}}{V_{R2}} \sum \left[ 2 \left( \frac{R_1}{R_2} \right)^{2} + \frac{1}{6} \left( \frac{V_0}{V_{R2}} \right) \frac{R_1}{R_2} \right] \]  
(5)

Here \( R_1 < R_2 \) and \( V_0 < V_{R2} < V_{R1} \).

If \( R_1 \approx 0 \), then \( \frac{V_{R2}}{V_{R1}} \approx \frac{2}{3} \left( 1 + \frac{V_0}{V_{R2}} \right) \frac{R_1}{R_2} \)  

According to these considerations, the ratio of the local speed to the transit speed is between 2/3 and 5/6. It is a function of the deceleration rate, the local speeds, and the background solar wind speed.

4 Acceleration of shocks

Table 5 shows seven shocks where the ratio \( V_b/V \) is more than one in Sheeley et al.’s (1985) list. The ratio of more than one means acceleration occurs during propagation. There is a possibility that this accelerations might result from a mis-identification of the associated CME. However, Woo et al. (1984) and Richter et al. (1985) noted a slight acceleration of the shock in the spacecraft radio scintillation measurements in situ Helios solar wind observations for the shock on July 31979 in Table 5. The average \( V_b/V \) is 1.14 ± 0.12 for the seven shocks.

The quiet solar wind speed, \( V_q \), at \( R \) astronomical units is given by \( V_q \sim 2V_r (\ln \frac{B}{B_\odot})^{1/2} \), where \( B = GMm/4kT, V_r = 2kT/m, M \) is the mass of the Sun, \( G \) is the universal gravitational constant, \( k \) is the Boltzmann constant, \( m \) is the sum of the proton and electron masses, and \( T \) is the temperature.

The ratio of local speed \( V_q \) and transit speed \( V_{qt} \) of the quiet solar wind is

\[ \frac{V_q}{V_{qt}} \sim 1 + \frac{1}{2} \left( \frac{V_0}{V_{R2}} \right)^{1/2} + \frac{3}{4} \left( \frac{V_0}{V_{R2}} \right)^{3/2} + \frac{15}{8} \left( \frac{V_0}{V_{R2}} \right)^{3/2} \]  
(6)

\[ \frac{V_q}{V_{qt}} \sim 1.2 \text{ for } R_1 \ll R. \]

This ratio is similar to the observed ratio for a continuously accelerating shock. This suggests possible interaction between the shock and the background solar wind.

5 Concluding remarks

We have developed an index that is useful for estimating the transit speed of interplanetary shocks by statistically analyzing in situ observations. The index is the ratio between the local speed and the transit speed and is between 0.6 and 0.9 for most observed shocks. It is between 0.3 and 0.7 after subtracting background solar wind speed. The radial distance dependence of this ratio is weak.

We applied a simplified shock propagation model and showed that it can explain the observational results. However, the ratio is affected by several factors: deceleration rate \( \alpha \), local shock speed \( V_s \), background solar wind speed \( V_b \), and so on. Calculation of the index for the MHD simulation results by Smith and Dryer (1990) showed good agreement with our results.

For the several shocks in Sheeley et al.’s (1985) list, the ratio is approximately 1.2. This suggests that these shocks were continuously accelerating while they transited from the Sun to Earth. This ratio of 1.2 is similar to the ratio calculated for the background solar wind acceleration. Gosling and Riley (1996) used the MHD simulation to show that slow CMEs accelerate in high-speed solar wind. Their analysis based on the CMEs identified in the Ulysses data (Gosling et al., 1994, 1995). Here we show the existence of continuously accelerating shocks even in slow-speed solar wind.

Associations between solar events and SC storms have been often made regardless of solar wind data. The relationship between transit speed and in situ shock speed discussed here and the relationship between bulk speed of solar wind and transit speed developed by Cliver et al. (1990) have the ability to verify associations.

<table>
<thead>
<tr>
<th>CME</th>
<th>Shock</th>
<th>Location (AU)</th>
<th>( \bar{V}_{\text{abs}} ) (km/s)</th>
<th>( \bar{V}_{\text{ins}} ) (km/s)</th>
<th>( \bar{V}_{\text{in}} ) (km/s)</th>
<th>( \bar{V}<em>{\text{abs}}/\bar{V}</em>{\text{in}} )</th>
<th>( (\bar{V}<em>{\text{abs}} - \bar{V}</em>{\text{in}})/\bar{V}_{\text{abs}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1979.05.27</td>
<td>1044</td>
<td>05.28</td>
<td>1840</td>
<td>0.43</td>
<td>560</td>
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<td>354</td>
</tr>
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<td>400</td>
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<td>0919</td>
<td>0.53</td>
<td>890</td>
<td>925</td>
<td>480</td>
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<tr>
<td>Average ± SD</td>
<td>0.64 ± 0.15</td>
<td>729 ± 137</td>
<td>848 ± 182</td>
<td>377 ± 57</td>
<td>1.14 ± 0.12</td>
<td>1.28 ± 0.21</td>
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between solar and interplanetary events. Use of these relationships can add confidence to solar event/SC storm associations.

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References


