**ABSTRACT**

Fast coronal mass ejections (CMEs) generate standing or bow shocks as they propagate through the corona and solar wind. Although CME shocks have previously been detected indirectly via their emission at radio frequencies, direct imaging has remained elusive due to their low contrast at optical wavelengths. Here we report the first images of a CME-driven shock as it propagates through interplanetary space from 8 \( R_\odot \) to 0.5 AU, using observations from the **STEREO** Heliospheric Imager. The CME was measured to have a velocity of \( \sim 1000 \) km s\(^{-1} \) and a Mach number of 4.1 \( \pm 1.2 \), while the shock front standoff distance (\( \Delta \)) was found to increase linearly to \( \sim 20 \) \( R_\odot \) at 0.5 AU. The normalized standoff distance (\( \Delta/D_O \)) showed reasonable agreement with semi-empirical relations, where \( D_O \) is the CME radius. However, when normalized using the radius of curvature, \( \Delta/R_O \) did not agree well with theory, implying that \( R_O \) was underestimated by a factor of \( \approx 3-8 \). This is most likely due to the difficulty in estimating the larger radius of curvature along the CME axis from the observations, which provide only a cross-sectional view of the CME.

**Key words:** shock waves – Sun: coronal mass ejections (CMEs)

**Online-only material:** animations

1. **INTRODUCTION**

Bow shocks occur when a blunt object moves relative to a medium at supersonic speeds (Rathakrishnan 2010). These shocks are formed across many scales and in different conditions; from astrophysical shocks such as planetary bow shocks (Slavin & Holzer 1981), or the shock at the edge of the heliosphere (van Buren et al. 1995), to shocks generated by the reentry of the Apollo mission capsules (Glass 1977). Coronal mass ejections (CMEs) which travel faster than the local fast magnetosonic velocity (with respect to the solar wind velocity) produce such standing shocks in the frame of the CME (Stewart et al. 1974a, 1974b). Interplanetary (IP) CME-driven shocks have previously been detected in radio observations as Type II bursts and using in situ measurements. Direct imaging of shocks, on the other hand, has remained elusive, primarily due to their low contrast (Liu et al. 2011; Vourlidas & Ontiveros 2009; Gopalswamy et al. 2008).

The shape, size, and standoff distance of a shock are controlled by several factors: the shape and size of the obstacle; the velocity difference between the obstacle and the medium with respect to the sonic speed (i.e., the Mach number); and the properties of the medium, such as the ratio of specific heats (\( \gamma \)) and the magnetic field. Relationships between the shock standoff distance and the Mach number have been derived by a number of different authors. The well-known semi-empirical relationship of Seiff (1962) has the form

\[
\frac{\Delta}{D_O} = 0.78 \frac{\rho_u}{\rho_d},
\]

which was derived for a spherical object, where \( \Delta \) is the shock standoff distance, \( D_O \) is the distance from the center to the nose of the obstacle, in this case the radius, and \( \rho_u \) and \( \rho_d \) are the densities upstream and downstream of the shock, respectively. Using gasdynamic theory, Spreiter et al. (1966) demonstrated that \( \rho_u/\rho_d \) could be written in terms of the upstream sonic Mach number, \( M_s \), and the ratio of specific heats \( \gamma \):

\[
\frac{\Delta}{D_O} = 1.1 \left( \frac{\gamma - 1}{\gamma + 1} \right) \left( \frac{M_s^2}{(\gamma + 1)(M_s^2 - 1)} \right)^{1/2}.
\]

The increase in the coefficient in the standoff relations from 0.78 to 1.1 is due to the fact that the object under consideration (Earth’s magnetosphere) in Equation (2) is more blunt than a sphere; specifically, it is an elongated ellipse. Neither Equation (1) nor Equation (2) behaves as expected at low Mach numbers, where the shock should move to a large standoff distance. A modification which corrects for this enables Equation (2) to be written in the form

\[
\frac{\Delta}{D_O} = 0.81 \left( \frac{\gamma - 1}{\gamma + 1} \right) \left( \frac{M_s^2}{(\gamma + 1)(M_s^2 - 1)} \right)^{1/2},
\]

where the additional term in the denominator ensures the shock moves to a large distance as the Mach number approaches unity (Farris & Russell 1994). They also suggested that using the obstacle radius of curvature rather than radius would be more suitable as it accounts for the shape of the obstacle, resulting in

\[
\frac{\Delta}{R_O} = 0.81 \left( \frac{\gamma - 1}{\gamma + 1} \right) \left( \frac{M_s^2}{(\gamma + 1)(M_s^2 - 1)} \right)^{1/2},
\]

where \( R_O \) is the obstacle radius of curvature.

In general, a conic section can be represented by \( y(x)^2 = 2R(D - x) + b(D - x)^2 \), where \( b \) is the bluntness (\( b < -1 \): blunt elliptic; \( b = -1 \): spherical; \( -1 < b < 0 \): elongated elliptic; \( b = 0 \): parabolic; \( b > 0 \): hyperbolic). The shape of the shock fronts is known to be represented by a modified conic section. One such parameterization of the shock front, from Verigin et al. (2003), is

\[
y^2(x) = 2R_s(D_S - x) + \left( \frac{D_S - x)^2}{M_s^2 - 1} \right)^{1/2} \left( 1+ \frac{b_s(M_s^2 - 1)}{1 + d_s(D_S - x)/R_s^2} \right),
\]
where $b_3$ is the bluntness of the shock and $d_3$ is related to the asymptotic downstream slope or Mach cone (see Figure 1).

The relationships between the standoff distance and the Mach number have been investigated from a number of perspectives, including numerical modeling, analytical relations, laboratory experiments, and in situ measurements of planetary bow shocks (Spreiter & Stahara 1995, 1980). These have shown that in general the semi-empirical relations provide a good description of shocks, with the low Mach regime being an exception (Verigin et al. 2003). Depending on the physical context, the sonic Mach number ($M_s$) can be replaced with the magnetosonic Mach number ($M_{MS}$), when dealing with plasmas such as the solar wind and CMEs. It has been shown that using gasdynamic relations when dealing with magnetized plasmas works well when the magnetohydrodynamic Mach numbers are high. It also provides a good approximation when the Alfvén ($M_A$) or fast magnetosonic ($M_{MS}$) Mach numbers are low and these Mach numbers are substituted for the gasdynamic ($M_s$) Mach numbers (Fairfield et al. 2001).

Standoff distances of CME-driven shocks have been investigated from an in situ perspective by many authors (e.g., Russell & Mulligan 2002; Lepping et al. 2008; Odstrcil et al. 2005). Russell & Mulligan (2002) found that the shock standoff distance ($\Delta$, thickness of magnetosheath) was of the order of 21 $R_\odot$ at 1 AU. Lepping et al. (2008) derived an average $\Delta$ of about 8 $R_\odot$ at 1 AU. However, when considering the CME radius (flux rope radius) as $D_o$, the typical $\Delta$ expected from Equation (3) is about 5 $R_\odot$ at 1 AU. Russell & Mulligan (2002) proposed that Equation (4) may be more suited as it accounts for the fact that the CME front may not be circular and that the radius of curvature at the nose is a dominant factor in determining the standoff distance. However, they found that Equation (4) did not fit the observations either and speculated this may be due to observational effect of only measuring one of the radii of curvature of the CME. The underlying structure of a CME is believed to be a flux rope which has two characteristic curvatures: a smaller one due to the curvature perpendicular to its axis (the radius when viewed as a cross section) and the larger curvature along the axis.

In this Letter, we investigate if the shock relations above hold for a CME-driven IP shock. Specifically, we use direct obser-
In order to compare with relations in Section 1, the data were transformed into a coordinate system centered on the CME. To accomplish this, each CME front was fit with an ellipse. The center coordinates of these fits were then used to collapse all the data on to a common coordinate system centered on the CME. The shock front was fit with Equation (5), which gave the shock properties such as the shock standoff distance \( \Delta \), the Mach number \( M \), and the radius of curvature at the nose of the obstacle \( R_O \). Figure 3(a) shows data and the initial fit, while Figure 3(b) shows the shifted data and the shock fit using Equation (5). The fast magnetosonic Mach number was calculated using \( M_{ms} = (v_{cme} - v_{sw})/v_{ms} \), where \( v_{cme} \) is the CME velocity, \( v_{sw} \) is the solar wind velocity, and \( v_{ms} \) is the fast magnetosonic speed. Since \( v_{sw} \) and \( v_{ms} \) were not known at the position of the CME, a model corona was used to evaluate them. This was based on the Parker solar wind solution with a simple dipolar magnetic field of the form \( B(r) = B_0(R_\odot/r)^3 \), where \( B_0 \) was 2.2 G at the solar surface (Mann et al. 2003). For each of the paired CMEs and shock observations, the standoff distances \( \Delta (=D_S - D_O) \) were obtained by three different means: (1) using the three-dimensional coordinates of the furthest point (max(\( h \)), where \( h = \sqrt{x^2 + y^2 + z^2} \) on the shock and the CME as \( h_{shk} \) and \( h_{cme} \), respectively, (2) the previous method can be applied but to the data in the common coordinate system which gave...
Figure 4. Shock properties derived directly from the observations (filled symbols) and from fits to the shock and CME (hollow symbols) as a function of time. (a) The maximum height of the CME front (triangles) and the shock front (circles) in CME-centered coordinate system. (b) The distance to the front of CME ($D_O$) and shock ($D_S$) in CME-centered coordinate system. (c) The shock standoff distance $\Delta$. (d) The normalized standoff distance ($\Delta/D_O$). (e) Standoff distance ($\Delta$) normalized by the radius of curvature of the CME ($R_O$). (f) The Mach number ($M$) derived from the CME velocity and model for the corona (filled circles) and from the fits to the shock front (hollow circles).

$D_O$ and $D_S$, and (3) the front fitting procedure also produced standoff distances. However, the results of method (1) cannot be used with the relations from Section 1 as they are not in a CME/obstacle-centered coordinate system, but the results from methods (2) and (3) can be compared to Equations (2)–(4).

3. RESULTS

A summary of the shock properties derived from the observations is shown in Figures 4(a)–(f) as a function of time. With the exception of the CME $h_{\text{cme}}$ and shock heights $h_{\text{shk}}$, all the properties have been derived from the data collapsed on to a common coordinate system with respect to the CME. The gap between the first three data points and others is a result of both the CME and shock leaving the COR2 FOV and entering the HI1 FOV. The contrast between shock and background in the first three and last three observations is extremely low, making identification of the shock difficult. As a result, these points are not reliable and should be neglected. Figure 4(a) shows the derived heights of the CME and shock as they were tracked from 8 $R_\odot$ to 120 $R_\odot$ (0.5 AU). Using a linear fit to $h_{\text{shk}} - h_{\text{cme}} (= \Delta)$ versus $h_{\text{cme}}$ (not shown), the extrapolated standoff distance at Earth was found to be $\sim 40 R_\odot$. Figure 4(b) shows the distance to the nose of the CME ($D_O$) and shock ($D_S$) front by filled symbols; also shown are the values derived from fits to the shock and CME front (hollow symbols). The increasing offset between the two is due to the differing centers of their coordinate systems, as one is elliptic and the other is parabolic. Figure 4(c) shows the standoff distance $\Delta$ derived using $D_O$ and $D_S$ (filled symbols) and from the fits to the fronts (hollow symbols). Both are in general agreement and show an increase with time. The standoff distance normalized using $D_O$ is shown in Figure 4(d). The normalized standoff distance is roughly constant with a mean value of 0.37 ± 0.09. The standoff distance normalized to the radius of curvature at the nose of the CME ($R_O$) is shown in Figure 4(e). The curvature could only be derived from the front fitting, as such only hollow data points are shown. Figure 4(f) then shows the magnetosonic Mach number ($M_{\text{MS}}$) derived using (1) the CME speed in conjunction with the coronal model (filled symbols) and (2) the shock front fitted using Equation (5) (hollow symbols). The mean Mach number from the coronal model was 3.8 ± 0.6, while a value of 4.4 ± 1.6 was found using the front fitting method. The mean Mach number from both methods was 4.1 ± 1.2.

Figure 5(a) shows the relationship between the normalized standoff distance ($\Delta/D_O$) and the Mach number ($M_{\text{MS}}$) for a number of models. The Mach numbers were calculated using the coronal model (filled symbols) and front fitting (hollow symbols). The normalized standoff distances were calculated using measured values of $D_O$ and $D_S$ (filled symbols) and fits
to the CME and shock fronts (hollow symbols). Both show good general agreement between our observations and the models (<20%). The model of Seiff (1962) shows the poorest agreement, although this is not unexpected as it was derived for a circular obstacle and the CME is quite blunt compared to a circle. Figure 5(b) shows the relationship between the standoff distance normalized by the radius of curvature of the CME ($\Delta/R_0$) and the Mach number for a number of models. In this case, $R_0$ can only be derived from the front fitting. These values are then plotted as a function of the Mach numbers derived using both methods described above (hence, each value of $\Delta/D_0$ appears twice). Our results do not agree with the expected relation (Equation 4) and indicate that the radius of curvature $R_0$ is underestimated by a factor of $\approx 3$–8. One possible reason for this is that we have not considered the effect of the magnetic field of the CME and solar wind effects on the shock. However, one would expect if this had a significant effect it would also affect the other relation. It should be noted that the fast magnetosonic velocity and sonic velocity calculated from our model differ by less than 7% after excluding the first three data points as mentioned earlier. This also suggests that the magnetic field should not play a major role. A more likely reason is due to an observational effect similar to that suggested by Russell & Mulligan (2002), where only one radius of curvature of the CME is observed. The observations provide a cross-sectional view of the CME along one of its axes. As a result, we have no information on the curvature along other CME axes.

4. DISCUSSION AND CONCLUSIONS

For the first time, we have imaged a CME-driven shock in white light at large distances from the Sun. The shock was tracked from $8 R_\odot$ to $120 R_\odot$ (0.5 AU) before it became too faint to be identified unambiguously. The CME was measured to have a velocity of $\sim 1000$ km s$^{-1}$ and a Mach number of 4.1 ± 1.2, while the shock front standoff distance ($\Delta$) was found to increase linearly to $\sim 20 R_\odot$ at 0.5 AU. The normalized standoff distance ($\Delta/D_0$) was found to be roughly constant with a mean of 0.37 ± 0.09. The normalized standoff distance derived using $D_0$ and $D_S$ and its relation to the Mach number ($M_{MS}$) were compared to previous relations and showed reasonable agreement. The normalized standoff distance ($\Delta/D_0$) and Mach number were also derived by fitting the CME and shock front, which agreed well with theory and our other method of estimation. The fitting also allowed us to test the CME radius of curvature ($R_0$) enabling us to test the relationship between $\Delta/R_C$ and the Mach number. In this case, the derived ratios did not agree with the theoretical predictions and showed a significant deviation.

The faint nature of the shock front made its identification challenging, and thus, the front location and characterization showed some scatter (Figure 4). For example, the Mach numbers in Figure 4(f) show a large amount of variability especially from the front fitting. The standoff distances in Figure 4(c) show the same trend and the two different methods give similar results. In should be noted that the first three and last three data points show large deviations from the rest of the data for a number of derived properties. These correspond to very low contrast observations, and hence should be ignored. The Mach number derived from our coronal model and CME position and speed and from the shock front fitting both agree. This is a good indication that our methods accurately describe the shock even in the presence of large uncertainties.

Both sets of data for the normalized shock standoff distance $\Delta/D_0$ versus the Mach number ($M_{MS}$) derived directly and from front fitting show good general agreement (Figure 5(a)). The standoff distance normalized by the CME radius of curvature ($\Delta/R_\odot$) versus Mach number ($M_{MS}$) from either the fits or derived directly does not agree with any of the relations (Figure 5(b)). Assuming that a CME can be modeled as a flux rope, it should have two radius of curvatures. Our observations are a measure of a combination of these, which depends on the orientation of the flux rope. This observational effect implies that we may only be measuring the smaller of the two and this leads to the underestimation of $R_0$. Finally, the general agreement between the Mach number derived from our model and the Mach number derived from the fits suggests that the fitting is not the source of the problem. Using a mean Mach number of 4 to get a value of 0.26 for $\Delta/R_\odot$ ratio and the standoff distance calculated at Earth ($40 R_\odot$), we can estimate the radius of curvature of this CME at Earth to be $150 R_\odot$ (0.7 AU).

Imaging observations of CME-driven shocks opens up a new avenue for studying their fundamental properties. This type of observation will be highly complementary to radio and in situ measurements. A complete picture of the shock could then be constructed and the derived properties from the different observations could be compared and contrasted. Furthermore, the analysis presented here will be applicable to future observations of shocks.

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