PREDICTING THE ARRIVAL TIME OF CORONAL MASS EJECTIONS WITH THE GRADUATED CYLINDRICAL SHELL AND DRAG FORCE MODEL

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ABSTRACT

Accurately predicting the arrival of coronal mass ejections (CMEs) to the Earth based on remote images is of critical significance for the study of space weather. In this paper, we make a statistical study of 21 Earth-directed CMEs, specifically exploring the relationship between CME initial speeds and transit times. The initial speed of a CME is obtained by fitting the CME with the Graduated Cylindrical Shell model and is thus free of projection effects. We then use the drag force model to fit results of the transit time versus the initial speed. By adopting different drag regimes, i.e., the viscous, aerodynamics, and hybrid regimes, we get similar results, with a least mean estimation error of the hybrid model of 12.9 hr. CMEs with a propagation angle (the angle between the propagation direction and the Sun–Earth line) larger than their half-angular widths arrive at the Earth with an angular deviation caused by factors other than the radial solar wind drag. The drag force model cannot be reliably applied to such events. If we exclude these events in the sample, the prediction accuracy can be improved, i.e., the estimation error reduces to 6.8 hr. This work suggests that it is viable to predict the arrival time of CMEs to the Earth based on the initial parameters with fairly good accuracy. Thus, it provides a method of forecasting space weather 1–5 days following the occurrence of CMEs.

Key words: solar–terrestrial relations -- Sun: coronal mass ejections (CMEs)

1. INTRODUCTION

A coronal mass ejection (CME) is a massive eruption of plasma threaded with a magnetic field from the Sun. A typical CME expels $10^{14}$--$10^{16}$ g of plasma and $10^{29}$--$10^{31}$ erg of kinetic energy (Howard et al. 1985) through the solar corona into interplanetary space. In some extreme cases, CMEs have speeds over 2000 km s\textsuperscript{-1} (Yashiro et al. 2004; Liu et al. 2014) and may reach Earth within a day if they are Earth-directed. CMEs are known to be a major source of interplanetary disturbances and are capable of influencing geomagnetic environments with shock waves, ejecta, and/or magnetic clouds (MCs) (see, e.g., Gosling et al. 1991; Gosling 1993; Webb et al. 1994; Burlaga et al. 1998; Koskinen & Huttunen 2006; Zhang et al. 2007). Some rare events with very strong ejecta magnetic fields, say, Dst $< -500$ nT, are potential hazards to spacecraft and some modern infrastructures (e.g., Carrington 1859; Cliver & Svalgaard 2004; Siscoe et al. 2006). Therefore, understanding the CME propagation and ultimately making an accurate forecast of CME arrival times are important issues in solar and space physics.

Since CMEs arrive at Earth within 1–5 days after they launch from the Sun (e.g., Brueckner et al. 1998; Gopalswamy et al. 2000), forecasting their arrival time with an accuracy of a dozen of hours is possible if we understand the key factors controlling the CME propagation. Usually, studying the propagation process of CMEs requires remote sensing images taken during the initial stages of CMEs and in situ observations when CMEs reach the Earth. However, with only the observations of the initial stages at hand, some simple models are usually adopted to study the follow-up propagation process of CMEs. Gopalswamy et al. (2000) developed a constant acceleration or deceleration model to account for the findings that fast CMEs experience a deceleration and slow ones tend to converge to the speed of the solar wind. Gopalswamy et al. (2001) further improved the model in which the acceleration ceases before 1 AU, accounting for the fact that slow CMEs have approximately the same transit time. This reduces the prediction error to 10.7 hr. More sophisticated approaches to CME kinematics consider the equation of motion governed by the drag force of the solar wind (Vršnak 2001b; Vršnak & Gopalswamy 2002; Borgazzi et al. 2009; Vršnak et al. 2010).

However, as can be seen in several validation studies (e.g., Owens & Cargill 2004; Colaninno et al. 2013; Vršnak et al. 2014), the kinematical model yields a prediction error of around 10 hr based on the data set available, which is not significantly improved compared to the constant acceleration/deceleration model. Thus, variants of the drag force model, with its parameters determined based on different aspects, have been further explored (Vršnak et al. 2004; Byrne et al. 2010; Hess & Zhang 2014; Möstl et al. 2014).

An important topic in space weather forecasting is the estimation of the speed profile of the CME during its propagation. In particular, for the kinematical model, the CME initial speed is of crucial importance. The speed of a CME during the initial process can either be measured directly from the CME fronts in coronal images, or can be derived by fitting the images taken from multi-perspectives such as the twin spacecraft STEREO A and B. The former method gives only the speed projected on the plane of sky. The latter, however, yields the true speed by using geometric triangulation techniques (Liu et al. 2010a, 2010b) and assuming that the leading edge in the images by different spacecraft corresponds to the same point. In the case of only one observer, some other geometric methods, e.g., the fixed-$\Phi$ fitting (Sheeley et al. 1999; Rouillard et al. 2008), the harmonic mean fitting (Lugaz 2010; Möstl et al. 2011), and the self-similar expansion fitting (Davies et al. 2012; Möstl & Davies 2013) have been adopted by further assuming a shape of the CME front.
However, such geometric modeling considers CME propagation only in the ecliptic plane that may incur large errors in estimating the CME initial speed. The cone model (Fisher & Munro 1984) and the Graduated Cylindrical Shell (GCS) model (Temsitien et al. 2006, 2009; Temsiien 2011) have also been used for a better estimation of CME speeds assuming a particular shape and self similarity of the CME. Although various models have been applied to case studies, previous statistical studies of a sample of CMEs were mostly restricted to the projection speeds with the drag model (e.g., Gopals­wamy et al. 2000, 2001; Owens & Cargill 2004). It is not accurate enough, either, to assume a radial propagation from the source region since the CME propagation trajectory sometimes deviates from the radial direction (e.g., Vršnak et al. 2014).

In this paper, we present a statistical study of 21 Earth-directed events. These events caused geomagnetic disturbances and serve as a good sample for testing the prediction method of CME arrival times to the Earth. The GCS model is applied to determine the CME initial speeds in a three-dimensional perspective. A fitting on the results of the transit time versus the initial speed with the drag force model shows a mean absolute error of 12.9 hr. In particular, five CMEs are identified for their angular deflections due to mechanisms other than the solar wind drag, such as interactions with the background magnetic field or with other CMEs. The exclusion of these events yields a much better prediction accuracy of about 6.8 hr.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. The CME Sample

CMEs have been observed for several decades, but only in recent years has it been possible to record the images of CME eruptions simultaneously from different perspectives, such as those by Solar and Heliospheric Observatory (SOHO; Domingo et al. 1995) and Solar Terrestrial Relations Observatory (STEREO; Kaiser et al. 2008). Among all the CMEs, the Earth-directed ones are of particular interest because they are potential causes of geomagnetic storms. An Earth-directed CME can be readily identified through the full- or half-halo shape (halo CME; Howard et al. 1982) in the coronagraph of SOHO. When a CME propagates into the interplanetary space, it is termed as an ICME and can probably be observed by in situ instruments to record parameters like the plasma density, speed, and magnetic field by the spacecraft Global Geospace Science WIND (Acuña et al. 1995) and Advanced Composition Explorer (Stone et al. 1998) at 1 AU when the CME approaches the Earth.

The twin spacecraft STEREO A and B are located separately and away from the Sun–Earth line, with A in an orbit ahead of the Earth and B behind the Earth. On board STEREO, the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI; Howard et al. 2008) contains two coronagraphs of COR1 and COR2 that continuously take white light images in the range of 1.5–4R_☉ and 2.5–15R_☉ and with time resolutions of 10 and 20 minutes, respectively. Along with the C2 and C3 instruments of the Large Angle Spectral Coronagraph (LASCO; Brueckner et al. 1995) on board SOHO that take white light images of a field of view (FOV) up to 32R_☉, the three coronagraphs provide a stereoscopic view of the CME and can track the CME front up to 15R_☉.

The data from the Heliospheric Imager (HI) on board STEREO is also used for verification of the interplanetary track of the CME. HI consists of two imagers. The FOV of HI1 is 20° × 20° centered at 14° elongation from the center of the Sun and HI2 has a 70° × 70° FOV centered at 53° from the center of the Sun. Thus, the instruments offer the possibility to track CMEs from near the Sun up to 1AU. Here, we employ J map techniques (Sheeley et al. 1999) to track the CME propagation and also verify whether a CME undergoes interactions with other CMEs.

In order to make a statistical study of the CME propagation times and test the drag force model, we employ the GMU CME/ICME list compiled by Phillip Hess and Jie Zhang (http://solar.gmu.edu/heliophysics/index.php/GMU_CME/ICME_List). We select the events with unambiguous shock fronts in the running difference images of COR2 and C2/C3. Our sample is comprised of the 21 events observed during 2008–2012 that are listed in Table 1. In the following, the 2012 October 5 event is used to demonstrate our data processing.

2.2. GCS Model and the CME Speed

The initial speed of a CME is determined based on the GCS model. First, the height of the CME apex (i.e., the shock front) is fitted with ray-trace programs. As is shown below, the GCS model provides a good morphological approximation to the CME and a relatively robust height measurement.

For a clear identification of the CME morphology, we use the running difference images from the three coronagraphs on STEREO A and B and SOHO (Figure 1). In total, we determine six parameters of the CME including the longitude, latitude, tilt angle, half-angular width, aspect ratio, and apex height that can best approximate the shape of the CME front. Except for the height, we assume that all the other five parameters do not change during the propagation of the CME, that is, the CME undergoes a self-similar expansion into space (Davies et al. 2012; Möstl & Davies 2013). The goodness of fit under a certain set of parameters is reflected by the similarity between the wire-frame fitted CME shape and the actual shape shown in observed images. For each event, we finally choose the best set of parameters that can ensure that the goodness of fit for the time sequence of the event is most favorable.

The best fit for the 2012 October 5 event (see Figure 1 and Table 2) gives a CME height of 10.72 R_☉ at 05:54 UT. Note that an automatic similarity test is conducted after the set of parameters is derived manually. The test examines the difference between the shape of the fitted wire frame and the observed CME profile shown in the images of STEREO A and B. For this event, the similarity reaches a level of 68.7%. The error of the six parameters is estimated by varying the corresponding parameter that results in a 10% change in similarity. The uncertainty of the height is of an order of less than 1R_☉. Compared to the relatively large FOV of COR2 (15 R_☉), the uncertainty in height is small. Thus, the height is a robust parameter in the GCS model fitting even though the other five parameters may involve relatively large uncertainties.

A good fit yields a height–time relationship for the CME propagating into space. In practice, we repeat the GCS fitting six times for each event and then make an average of the fitted parameters. The height–time curve for the 2012 October 5 event is shown in Figure 2. The error bars represent the standard deviation of the six measurements. The initial speed of the CME is then obtained through a linear fit to the curve.
assuming that the CME has already reached a static speed in the FOV of COR2 (Zhang & Dere 2006). For this event, \( v_{\text{init}} \) is 558 ± 21 km s\(^{-1}\). The error refers to the 3σ uncertainty of the linear fitting.

2.3. Transit Time

The CME transit time is the time elapsed from the occurrence of the CME to its arrival at 1 AU. This parameter can be directly obtained from the in situ data by \( WIND \) (see Figure 3). In the 2012 October 5 event, a clear shock is seen at 05:00 UT on October 8, as indicated by the sudden jumps in the proton density, speed, and temperature (as denoted by the vertical dashed line in the figure). Behind the shock is a sheath region with enhanced proton density and temperature, and variable magnetic field. An MC (Burlaga et al. 1981) is thus identified by a strong magnetic field, a smooth rotation of the field, and a depressed proton temperature (marked by the shaded region). The MC ends at 17:00 UT on 2012 October 9. A connection between the CME in remote sensing images and the ICME observed in situ can be established with the HI data in the form of monthly movies or J maps. Thus, the transit time is calculated to be the time between the first appearance of the CME in the COR2 FOV and the detection of a shock near the Earth.

3. STATISTICAL RESULTS AND PREDICTION MODELS

Using the methods described above, we derive the initial speed and the transit time for 21 CME events in our sample. Figure 4 plots the two parameters showing a close relationship between them. Note that the 2012 October 5 event and the other three events serve as demonstrations in the following sections. As expected, the faster the CME’s initial speed, the shorter the time it takes for the CME to propagate to the Earth, which is consistent with previous observations (Gopalswamy et al. 2001). There is also a fairly large scatter of the data points, as shown in Figure 4. Besides the measurement errors in the speed and transit time, the CME may encounter different forces (such as angular forces exerted by the background magnetic field and CME–CME interactions) as discussed below.

3.1. The Drag Force Model

In general, CMEs interact with the solar wind in three perspectives: the Lorentz force on the plasma and the threaded magnetic flux rope, the gravity, and the drag force (Chen 1996). Compared with the drag force, the other two can be neglected (Vršnak & Gopalswamy 2002), given the reduction of the magnetic field in the heliosphere (Chen 1989; Vršnak 1990, 2001a) and the low density of CMEs (Vršnak 2001b). Thus, the drag force by the solar wind is a dominant force controlling the propagation of CMEs in the interplanetary space.

By considering the one-dimensional problem, the equation of motion can be expressed as

\[
\frac{dv}{dt} = -\gamma (v - w) |v - w|^{\beta - 1}. \tag{1}
\]

Table 1

List of the CME Events Studied in This Work

| #  | Onset Time\(^a\) | \( v_{\text{init}} \)\(^b\) (km s\(^{-1}\)) | Lon\(^c\) (°) | Lat\(^d\) (°) | \( \varphi \) (°) | ICME Start\(^e\) | Type\(^f\) | Transit Time (hr) |
|----|-----------------|-----------------|-------------|-------------|-------------|----------------|----------|-----------------|
| 1  | 2008 Dec 12 08:37 | 363 ± 23        | 6           | 7           | 20          | 2008 Dec 17 02:00 | EJ       | 113.4           |
| 2  | 2010 Apr 03 09:54 | 864 ± 7         | 6           | -25         | 38          | 2010 Apr 05 08:00 | SH + MC  | 46.1            |
| 3  | 2010 Apr 08 03:39 | 512 ± 34        | -16         | 0           | 28          | 2010 Apr 11 12:00 | SH + EJ  | 80.3            |
| 4  | 2010 Jun 16 14:39 | 222 ± 2         | -21         | 2           | 25          | 2010 Jun 20 20:00 | EJ       | 101.3           |
| 5  | 2010 Dec 23 05:39 | 287 ± 9         | 18          | -22         | 22          | 2010 Dec 28 04:00 | EJ       | 118.3           |
| 6  | 2011 Feb 15 02:24 | 769 ± 12        | 6           | -11         | 50          | 2011 Feb 18 03:00 | MC + CIR | 72.6            |
| 7  | 2011 Mar 25 05:39 | 90 ± 3          | -34         | 0           | 21          | 2011 Mar 29 16:00 | SH + EJ  | 106.3           |
| 8  | 2011 Aug 04 03:49 | 1512 ± 90       | 26          | 21          | 67          | 2011 Aug 15 09:00 | SH       | 38.4            |
| 9  | 2011 Sep 14 00:39 | 678 ± 13        | 2           | 13          | 75          | 2011 Sep 09 15:00 | SH + EJ  | 64.1            |
| 10 | 2011 Oct 22 10:39 | 882 ± 4         | 68          | 57          | 90          | 2011 Oct 24 18:00 | SH + MC  | 55.4            |
| 11 | 2012 Oct 27 12:39 | 795 ± 52        | -36         | 25          | 32          | 2011 Nov 01 08:00 | SH       | 115.3           |
| 12 | 2012 Jan 19 14:54 | 1299 ± 16       | -27         | 42          | 66          | 2012 Jan 22 05:00 | SH       | 62.1            |
| 13 | 2012 Mar 05 03:54 | 1237 ± 50       | -56         | 29          | 63          | 2012 Mar 08 11:00 | SH + EJ  | 79.1            |
| 14 | 2012 Mar 13 17:39 | 1616 ± 17       | 51          | 18          | 78          | 2012 Mar 15 13:00 | SH + EJ  | 43.4            |
| 15 | 2012 Mar 30 15:24 | 654 ± 8         | -56         | 30          | 31          | 2012 Apr 04 22:00 | EJ       | 126.6           |
| 16 | 2012 Apr 19 15:39 | 607 ± 15        | -24         | -30         | 50          | 2012 Apr 23 02:30 | EJ + CIR | 82.8            |
| 17 | 2012 Jul 12 16:39 | 1224 ± 14       | 0           | -11         | 56          | 2012 Jul 14 17:00 | SH + MC  | 48.4            |
| 18 | 2012 Sep 28 00:39 | 1104 ± 112      | 29          | 10          | 57          | 2012 Sep 30 23:00 | SH + EJ  | 70.3            |
| 19 | 2012 Oct 05 03:39 | 558 ± 21        | 9           | -20         | 35          | 2012 Oct 08 05:00 | SH + MC  | 73.3            |
| 20 | 2012 Oct 27 16:54 | 340 ± 28        | 12          | 10          | 37          | 2012 Oct 31 15:00 | SH + MC  | 94.1            |

Notes.

\( ^a \) Date and time (UT) of the first appearance in the COR2 FOV.

\( ^b \) Initial speed.

\( ^c \) Longitude of the propagation direction fitted by the GCS model. Earth is at 0° longitude; angles >0° correspond to solar west.

\( ^d \) Latitude.

\( ^e \) Equivalent half-angular width of the CME (see Sections 2.2 and 3.3 for details).

\( ^f \) Arrival date and time (UT) of the associated ICME.

\( ^g \) ICME properties. CIR: co-rotating interaction regions; EJ: ejecta; MC: magnetic cloud; SH: shock.

3
The exponent $\beta$ describes the drag regime; usually $\beta$ can vary in the range of 1–2, with $\beta = 1$ for the viscous and $\beta = 2$ for the aerodynamics regime (Byrne et al. 2010).

The parameter $\gamma$ is expressed as $\gamma = C_d A \rho_0 / m$ (Vršnak et al. 2010), where $C_d$ is the drag coefficient, $m$ is the mass, and $A$ is the cross-section of the CME. We take $C_d$ as a constant of the order of unity (Cargill 2004). Assuming that CMEs undergo a self-similar expansion into space, the cross-section can be calculated as $A \approx \pi (r \varphi)^2 / 4$, where $\varphi$ is the half angle and $r$ is the height of the center of the CME shell. The solar wind density can be given by the empirical formula $\rho_0 \approx \rho_1 / (r / R_{\odot})^2$ (Leblanc et al. 1998), where $\rho_1$ is the empirical solar wind density at 1 AU. Therefore, $\gamma \approx C_d R_{\odot}^2 \rho_1 \varphi^2 / 4m \propto \varphi^2 / m$. According to the GCS model, most of the CME mass is concentrated on the surface of the shell. Thus, $\varphi^2 / m$ does not change with CME propagation and is proportional to the initial surface density of the CME, which, for simplicity, we regard as nearly the same for different CMEs. Therefore, the parameter $\gamma$ is a constant in our modeling. However, in previous work (e.g., Vršnak & Gopalswamy 2002; Byrne et al. 2010), the parameter $\gamma$ is taken to be inversely related to the CME height. This relation is found statistically from SOHO data within the FOV.

Table 2

| $\text{Lon}^a$ (°) | $\text{Lat}^b$ (°) | $\Gamma^c$ (°) | $\alpha^d$ (°) | $\kappa^e$ | $H^f (R_{\odot})$ |
|-------------------|-------------------|----------------|----------------|-----------|------------------|
| $54.4^{+28.0}_{-7.0}$ | $-17.3^{+34.8}_{-17.3}$ | $39.1^{+13.3}_{-12.7}$ | $27.4^{+13.5}_{-12.7}$ | $0.410^{+0.11}_{-0.12}$ | $10.72^{+1.93}_{-0.18}$ |

Notes.

$^a$ Carrington longitude.

$^b$ Latitude.

$^c$ Tilt angle respect to the equator, with counterclockwise being positive.

$^d$ Half-angular width between the two legs of the model.

$^e$ Aspect ratio.

$^f$ CME apex height.

Figure 1. Running difference images of the 2012 October 5 CME at 05:54 UT. In the bottom row, the fitted GCS model is overlaid as the green wire frame.

Figure 2. Height vs. time curve of the 2012 October 5 event. The height refers to that of the CME apex obtained by the GCS fitting. The error bar indicates the standard deviation from six independent measurements. The initial speed $v_{\text{init}} = 558 \pm 21 \text{ km s}^{-1}$ is obtained through a linear fit to the curve.
of LASCO C3 of 30 $R_\odot$ (Vršnak 2001b), so it may not work for CME propagation in the interplanetary space.

The equation of motion can then be integrated analytically to yield

$$x_\beta = wt \pm \frac{1}{\gamma (2 - \beta)} \left\{ |v_{\text{init}} - w|^\beta - \left[ \gamma (\beta - 1) t + |v_{\text{init}} - w|^\beta \right]^{\gamma/\beta} \right\},$$

where $1 < \beta < 2$, and the first positive sign is for $v_{\text{init}} > w$, and the first negative sign is for $v_{\text{init}} < w$. In particular, for the pure viscous ($\beta = 1$) regime, we have

$$x_1 = wt + \frac{1}{\gamma} (v_{\text{init}} - w) \left( 1 - e^{-\gamma t} \right),$$

and for the pure aerodynamic ($\beta = 2$) regime, we get

$$x_2 = wt + \frac{1}{\gamma} \ln \left( \frac{v_{\text{init}} - w}{t + 1} \right).$$

In what follows, we refer to Equation (2) as the hybrid (drag force) model, as discriminated from the viscous model by Equation (3), and the aerodynamics model by Equation (4).

Given a certain set of parameters $\gamma$, $\beta$, and $w$, the equation of motion can be solved to yield the relationship between the initial speed and the transit time at 1 AU. Thus, the theoretical transit time can be expressed as $T = T(v_{\text{init}}; \gamma, \beta, w)$. We then get the parameters $\gamma$, $\beta$, and $w$ by fitting the measured initial speed versus transit time from the sample with the theoretical relationship.

### 3.2. Fitting Results for the Whole Sample

We first fit the transit time–initial speed distribution for the whole sample using the drag force model, as shown in Figure 5. We implement the nonlinear least absolute curve fitting with the Levenberg–Marquardt algorithm (Markwardt 2009). This technique allows faster convergence to the local minimum, but also depends on the initial value of the parameters. Considering the possible
existence of several local minima in fitting errors, we choose the initial values from the parameter space to ensure that the final error is the smallest. However, after several test runs, we found that the mean absolute error in the prediction of transit time (|Δτ|) varies little (less than 0.1 hr) subject to the change in the parameters. Therefore, as explained above, despite the mathematical difficulty, the fitted parameters should result in a reasonable solution.

The parameters obtained from the fitting are listed in Table 3. Fitting with the hybrid model gives a mean absolute error ⟨Δτ⟩ = 12.9 hr. Here Δτ is defined as the difference between the predicted transit time and the observed one; therefore, Δτ < 0 refers to cases in which the former is somewhat shorter than the latter. We also calculate the average value of the time difference, termed as the mean error ⟨Δτ⟩, which represents a systematic deviation of the observed transit time from the theoretical one. It may be caused by some physical processes that cannot be described in terms of the drag force model. For the hybrid model, ⟨Δτ⟩ = −7.1 hr. The fitting by the pure viscous and aerodynamic models both give ⟨|Δτ|⟩ = 13.2 hr, with ⟨Δτ⟩ = −5.1 hr and −9.9 hr, respectively.

### 3.3. Fitting Results for a Restricted Sample

The three-dimensional propagation of a CME is largely related to the ambient environment. A non-uniformly distributed coronal magnetic field may result in an asymmetric or non-radial motion of the CME in the early stage of propagation (e.g., MacQueen et al. 1986; Gopalswamy & Thompson 2000; Kilpua et al. 2009; Shen et al. 2011; Panasenco et al. 2013). A CME can also be deflected during its propagation in the interplanetary space when interacted with the non-radial magnetic backgrounds with the deflection angle dependent on the speed of the CMEs (e.g., Wang et al. 2004, 2014). The drag force model cannot be reliably applied to CMEs with such events with non-radial forces. Here we denote by θ the propagation angle of a CME, which is the angle between the central axis of the CME and the Sun–Earth line, and by ϕ the CME half-angular width. In principle, a CME with ϕ < θ that propagates radially and self-similarly initially should not encounter the Earth; however, it might reach the Earth through angular deflections. Such events may worsen the fitting results and should be analyzed separately.

The half angle ϕ of a CME is calculated based on the cone model instead of the GCS model in order to reduce the number of free parameters. Since the tilt angle Γ, half angle α, and aspect ratio κ in the GCS model are partially degenerated and each of them involves a large measurement error (see Table 2 for the error derived from a similarity test), we combine these three parameters into one, which just corresponds to the half angle in the cone model. From the definition of the GCS model (Thernisien et al. 2009), we may derive that

$$\varphi \approx \sqrt[4]{\alpha (\alpha + \delta) \kappa},$$

where κ = sin δ and Γ is eliminated.

As mentioned above, those events with the criteria ϕ < θ may undergo obvious interactions with non-radial forces that make their propagation direction largely deviate from radial. After a careful examination, we seek out five events that possibly belong to this category and exclude them in the sample of CMEs. We then redo the fitting of the viscous, hybrid, and aerodynamics modeling to the measured results of the remainder 16 events, as is shown in Figure 6. Note that most of the filtered-out events (4 out of 5) deviate largely from the theoretical curve, implying that the drag force models do not apply to them. With the restricted sample, the estimation errors are 8.0, 6.8, and 6.7 hr for the viscous, hybrid, and aerodynamics models, respectively.

We can see that the estimation error by the aerodynamics model and that by the viscous model are equally large when using the original sample. However, both of them are significantly improved if we instead use the restricted sample. Comparatively, the aerodynamics model yields an even smaller estimation error. Thus, the aerodynamics drag might play an important role in the solar wind drag in interplanetary space. The hybrid model, however, fails to produce a more accurate estimation, even with one more extra free parameter than the

### Notes.

a Parameters obtained by fitting the whole sample including 21 CME events.
b The coefficient proportional to the strength of the drag force.
c The exponent on the difference of speed of the CME and the solar wind.
d The solar wind speed.
e The mean absolute error between the observed transit time and the predicted one.
f Parameters obtained by fitting the restricted sample including 16 CME events.

**Table 3**

Best Fitted Parameters of the Drag Force Model

| Parameter | Viscous | Hybrid | Aerodynamics |
|-----------|---------|--------|--------------|
| Whole Sample<sup>a</sup> | γ<sup>b</sup> | 1.12 ± 0.06 x 10<sup>-5</sup> | 1.30 ± 0.04 x 10<sup>-6</sup> | 3.02 ± 1.15 x 10<sup>-8</sup> |
| | β | 1 | 1.37 ± 0.67 | 2 |
| | w | 477 ± 48 | 501 ± 41 | 549 ± 36 |
| | | | | |
| Restricted Sample<sup>b</sup> | γ | 0.90 ± 0.39 x 10<sup>-5</sup> | 1.10 ± 0.27 x 10<sup>-7</sup> | 2.71 ± 0.67 x 10<sup>-8</sup> |
| | β | 1 | 1.76 ± 0.85 | 2 |
| | w | 488 ± 34 | 546 ± 26 | 558 ± 30 |
| | | | | |

Notes.

<sup>a</sup> The coefficient proportional to the strength of the drag force.
<sup>b</sup> Parameters obtained by fitting the whole sample including 21 CME events.
<sup>c</sup> The exponent on the difference of speed of the CME and the solar wind.
<sup>d</sup> The solar wind speed.
<sup>e</sup> Parameters obtained by fitting the restricted sample including 16 CME events.
motion of the CMEs. Since in these two events the angular width of the CME is less than the propagation angle, interactions with a previous CME might cause the propagation direction deviating from radial. In contrast, the 2012 July 12 and the 2012 October 5 events do not show significant interplanetary interactions, so the drag force model can be reliably applied to such cases.

4. DISCUSSION AND CONCLUSION

In this paper, we statistically study the transit time (between the Sun and the Earth) against the initial speed for a sample including 21 CME events directed toward the Earth. For each event, the in situ signal clearly shows at least one of the three identities (shock, ejecta, or MC) for a typical ICME, ensuring that the CME does actually reach the Earth and disturb the geomagnetic environment. The initial speeds of these CMEs cover a range from 90 to 1616 km s\(^{-1}\), which is sufficiently wide to cover both slow and fast ones.

The initial speed of an event is determined by the GCS model fitting the images obtained from COR2 on board STEREO A and B and C2/3 on board SOHO. The images from three viewing angles offer a much better accuracy when determining the CME height and velocity, which are, in particular, free from the projection effect.

The drag force model is then applied to fit the transit time versus the initial speed distribution. We achieve mean absolute errors of 13.2, 12.9, and 13.2 hr for the viscous, hybrid, and drag force models, respectively. These values are comparable with previous results (e.g., Gopalswamy et al. 2001; Owens & Cargill 2004; Colaninno et al. 2013; Vršnak et al. 2014). However, since the drag force model considers only the radial drag force exerted by the solar wind, it cannot apply to those events that undergo interplanetary interactions with other CMEs and whose propagation direction clearly deviates from radial. We pick out five events that likely belong to such a category and exclude them in the statistical sample. Doing so greatly improves the prediction accuracy. The estimation error of the transit time is reduced to 8.0, 6.8, and 6.7 hr for the three models, respectively, using the restricted sample. Moreover, the result shows that the higher order aerodynamic model achieves a better prediction than the pure viscous model. If using the hybrid model, the best fitted exponent is 1.76, suggesting that the solar wind drag is a combination of the two CME–CME interactions can slow down the CME propagation speed.

3.4. Verifying the Interplanetary Propagation of CMEs

We check in detail four representative events in our sample. The 2011 October 27 event has an observed transit time of 115.3 hr. The predicted transit time based on the three models, however, is less than 80 hr. Such a discrepancy suggests that the predicted propagation speed is clearly higher than the actual one. The J map, which is constructed from the running difference images along the ecliptic plane by STEREO A, is shown in Figure 7. The figure reveals two CMEs indicated by the two arrows, the second of which is actually the event included in our sample, starting at 12:39 UT. One can clearly see that the faster one (noted as CME-2) catches up with the previous slower one (noted as CME-1) at a place (shown as the boxed region) where they undergo an interaction. Thus, an extra resistance force other than the solar wind drag should be exerted on the faster CME we are tracking. A similar process is also shown in the 2012 March 30 event. Another possible result of the interactions is the angular
the possible angular deflections of the CMEs at the initial stage in the lower corona. A stereoscopic determination of the CME morphology and propagation are thus needed to deduce the CME initial speed. This is the main reason why we can achieve a somewhat better prediction accuracy compared with previous studies. Our method is based on observations in the earlier process of the CME propagation, which is within the FOV of COR2 (15 \( R_E \)). Thus, our method can be used to forecast the CME arrival time once the event has erupted. However, a better estimation accuracy may be achieved by tracking the event for an extended distance with HI (e.g., Möstl et al. 2014).

The three-dimensional nature of the CME morphology also adds to the uncertainties in the transit time estimation. Since CMEs have a finite angular width, those with a propagation direction slightly deviated from the Sun–Earth line may still encounter the Earth at some off-axis point. In this case, the CME forehead may have traveled a distance larger than 1 AU. Therefore, a correction based on the angular width and propagation angle of the CME is needed (Shen et al. 2014). For example, typical parameters of \( \varphi = 45^\circ \) and \( \theta = 10^\circ \) give \( \Delta t \approx 1.8 \) hr, while \( \varphi = 60^\circ \) and \( \theta = 30^\circ \) result in \( \Delta t \approx 15.5 \) hr for the correction to the transit time.

Observations have also revealed that many CMEs have two different fronts of a bubble-shaped structure and a flux-rope-shaped structure (Kwon et al. 2014). In our study, we only model the outermost front seen in the running difference images. Thus, confusion between the two fronts, whose speeds differ, is possible, and may also affect accuracy when determining the CME initial speed.

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