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An empirical model to predict the 1-AU arrival of interplanetary shocks

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Abstract

We extend the empirical coronal mass ejection (CME) arrival model of Gopalswamy et al. [Gopalswamy, N. et al. Predicting the 1-AU arrival times of coronal mass ejections, J. Geophys. Res. 106, 29207, 2001] to predict the 1-AU arrival of interplanetary (IP) shocks. A set of 29 IP shocks and the associated magnetic clouds observed by the Wind spacecraft are used for this study. The primary input to this empirical shock arrival model is the initial speed of white-light CMEs obtained using coronagraphs. We use the gas dynamic piston–shock relationship to derive the ESA model which provides a simple means of obtaining the 1-AU speed and arrival times of interplanetary shocks using CME speeds.

Keywords: Space weather; Interplanetary shocks; Predicting interplanetary shock arrival; Coronal mass ejections

1. Introduction

The severest of geomagnetic storms are caused by coronal mass ejections (CMEs) (Gosling, 1993). These CMEs often drive interplanetary (IP) shocks that impart the first pressure pulse on the magnetosphere resulting in storm sudden commencements (e.g., Chao and Lepping, 1974). IP shocks are also known to accelerate solar energetic particles throughout the IP medium including the energetic storm particles that are potentially hazardous to humans in space (e.g., Reames, 1999). Predicting these shocks has been one of the active efforts in the field of solar–terrestrial relationship (Schwenn, 2000; Smith et al., 2003). Recently, we developed an empirical CME arrival (ECA) model to predict the 1-AU arrival of Earth-directed CMEs using coronagraphic and in situ observations (Gopalswamy et al., 2000, 2001). The main input to this model is the initial speed of the CMEs obtained remotely by white-light observations. In this paper, we extend this CME arrival model to predict the shock arrival at 1 AU using the piston–shock relationship between magnetic clouds and IP shocks. We use a set of 29 IP shocks detected in situ at 1 AU and the associated CMEs near the Sun observed by the Solar and Heliospheric Observatory (SOHO) mission's Large Angle and Spectrometric Coronagrpah (LASCO) to compare the model with observations.

2. The CME arrival model

The ECA model is based on two-point measurements (speed and onset times): (i) near the Sun by remote sensing and (ii) near Earth by local sensing. Gopalswamy et al. (2001) postulated that CME speeds change due to interaction with the solar wind resulting in an average acceleration (a) that depends linearly on the CME initial speed (u)

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$$a = 2.193 - 0.0054u. \quad (1)$$

This relationship was obtained from coronal and interplanetary observations of CMEs by spacecraft in quadrature (Gopalswamy et al., 2001). Assuming that the acceleration behaves the same way most of the time, the CME arrival time was obtained from the kinematic relation

$$S = ut + 1/2at^2, \quad (2)$$

where t is the travel time of the CME from the Sun to a distance S. Acceleration may not act all the way to 1 AU: once a slow CME attains the speed of the solar wind, the acceleration has to cease ($a \sim 0$). Fast CMEs may continue to decelerate beyond 1 AU. Therefore, the assumption of constant acceleration is not a good one. Gopalswamy et al. (2001) modified the profile of the acceleration such that it satisfied Eq. (2) up to a distance d_1 and ceased after that so the CME speed remained constant for the remaining distance d_2 to 1 AU. Thus the travel time $t = t_1 + t_2$, where t_1 and t_2 are the time taken by the CME to traverse d_1 and d_2, respectively:

$$t_1 = [-u + (u^2 + 2ad_1)^{1/2}]/a, \quad (3)$$

and

$$t_2 = d_2/(u^2 + 2ad_1)^{1/2}. \quad (4)$$

This model can also provide an estimate of the CME speed at 1 AU from the kinematic relation

$$v^2 = u^2 + 2ad_1, \quad (5)$$

where v is the speed at d_1 and remains the same at 1 AU because there is no acceleration beyond d_1. Eqs. (3) and (4) with Eq. (1) constitute the ECA model. Eq. (5) with Eq. (1) constitutes the model to predict the 1-AU speed of CMEs. Gopalswamy et al. (2001) considered d_1 values between 0.7 and 0.95 and showed that Eqs. (3) and (4) can be used to predict the arrival of CMEs with an error of ±10.7 h for a typical value of d_1 = 0.76 AU.

3. Approach to shock prediction

CMEs arrive at Earth with or without shocks, but those with shocks are generally more energetic. If the solar wind plasma is swept up faster than the Alfven speed, a fast mode MHD shock forms at a distance known as the standoff distance determined by the geometry of the driving CME and the upstream Alfvenic Mach number. The fast mode MHD shock is similar to the gas dynamic shock. The CME can be considered as the driver of the shock so that we use the gas dynamic relationship between the piston speed v_p and the speed of the shock (v_{sh}) ahead of the CME (see, e.g., Landau and Lifshitz, 1987):

$$v_{sh} = v_p(\gamma + 1)/2, \quad (6)$$

where γ is the ratio of specific heats. Knowing v_p from Eq. (5), we can get v_{sh}. For a strong shock, the positions of the shock (R_{sh}) and the piston (R_p) have the same ratio as v_{sh}/v_p. The standoff distance is given by the spatial separation between the shock and the piston:

$$\Delta R = R_{sh} - R_p = R_p(\gamma - 1)/2. \quad (7)$$

The standoff distance can then be converted to the shock lead-time (or standoff time), Δt

$$\Delta t = \Delta R/v_p. \quad (8)$$

In an in situ observation, a spacecraft will first encounter an IP shock and after a time Δt, it will encounter the driving CME. In the past such driving CMEs were referred to as "driver gas". It is thus possible to use the piston–shock relationship to obtain the 1-AU speed and arrival time of shocks. The shock travel time we need is nothing but ($t_1 + t_2 - \Delta t$), given by Eqs. (3), (4), and (6). The inputs needed to get Δt are the size of the driving CME (R_p) and its 1-AU speed. R_p can be identified as the radius of curvature of magnetic clouds, obtained from multi-spacecraft observations (0.3–0.5 AU, see Burlaga et al., 1990). v_p can be obtained from the model Eq. (5). For shocks in general, where the magnetic field may be important, one can use the following relation (see, e.g., Bennett et al., 1997):

$$\Delta R = 1.1R_p[(\gamma - 1)M^2 + 2]/[(\gamma + 1)M^2], \quad (9)$$

where M is the upstream magnetosonic Mach number. In this paper, we shall use the simpler gas dynamic relation (8).

4. Observations

In order to illustrate the method described above, we have chosen all the shock-associated magnetic cloud (MC) events detected and analyzed by the Wind Magnetic Field Investigation (MFI) team from the launch of Wind to May 2002 (see Table 1). Many of these events were also included in previous studies (Gopalswamy et al., 2000, 2001). For each event, the shock date and time, speed and upstream Alfvenic and magnetosonic Mach numbers are listed in columns 1–5, respectively. The time of arrival, speed (km/s) and transit time (DT in hours) of MCs are listed in columns 7–9. The date, onset time, speed (km/s), width ($W = H$ for halo and PH for partial halo), and the heliographic location of the corresponding white-light CMEs observed by SOHO/LASCO are listed in columns 10–14. In the last column, we have given the reference for information on the MCs. The 1-AU onset times of the shocks and those of the following MCs were obtained from the Wind data.