On the arrival times of halo Coronal Mass Ejections in the vicinity of the Earth

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Abstract It is well known that the arrival times of Coronal Mass Ejections (CMEs) in the vicinity of the Earth play an important role for solar terrestrial environment. It is necessary to predict the CMEs arrival time at 1 AU, for the better forecasting of space weather. Here, using LASCO halo CMEs data of 248 events observed during time period 1996–2007, we have tried to predict the arrival times as accurately as possible of full halo CMEs only. We have also studied arrival time of halo CMEs associated with type II radio bursts and X-class soft X-ray bursts, separately. In this paper we discussed about location and speed of Earth directed CMEs. The results obtained in the present investigation are discussed in the light recent scenario of CMEs understanding.

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1. Introduction

It is now well-known that space weather is significantly controlled by Coronal Mass Ejections (CMEs) which can affect our Earth environment in many ways (Gopalswamy, 2006; Gopalswamy et al., 2007; Iyer et al., 2006; Srivastava, 2006; Dumbovic et al., 2015). CMEs originating close to the central meridian of the Sun directed towards the Earth are the most geoeffective one with the biasing of source region to the western hemisphere. For space weather forecasts (geomagnetic storms, hazards to humans in space, effects on satellites, radio communication, GPS satellite errors, geomagnetic induced current, aurora) it is very important to know when a solar disturbance would reach the Earth (Srivastava and Venkatakrishnan, 2004; Gopalswamy et al., 2008). CMEs are dynamically expelled and driven by the coronal magnetic fields which decrease during their passage through the interplanetary space where some other processes (such as magnetic flux, current sheath, shocks) may accelerate them. These CMEs interaction with the ambient solar wind may provide the necessary drag for acceleration or de-acceleration of CMEs depending on their speeds (see e.g., Michalek et al., 2004; Manoharan et al., 2004 and references therein).

On combining CME observations made by SOHO/LASCO and interplanetary CMEs (ICMEs) (main causes for geomagnetic storms) measurements near the Earth, Gopalswamy et al. (2001), developed an empirical model to predict the arrival time of CMEs at 1-AU. They postulated that CMEs undergo an effective acceleration mechanism due to

interaction with the solar wind. This effective acceleration was assumed to be constant over the Sun–Earth distance and was defined as the difference between the initial (u) and final (v) speeds divided by the time (t) taken by a given CME to reach the Earth. They found a definite correlation between the effective acceleration (a) and initial speed (u) which is given below:

$$a_1 = 1.41 - 0.0035u \tag{1}$$

They improved their model by taking into account the projection effects which now becomes,

$$a_2 = 2.193 - 0.0054u \tag{2}$$

Here a_1, a_2 and u are in units of km/s^2 and km/s, respectively.

These relations can be used in the kinematics equation,

$$S = ut + \frac{1}{2}at^2 \tag{3}$$

where S is the distance travelled by the CME to predict arrival time at 1-AU. Their model involves only one free parameter, ''namely, the initial speed of CMEs''. With some modifications, they were able to predict the travel time within an error of 10.7 h.

Michalek et al. (2004) used a better method to obtain the space speed (the speed with which the CME spreads in the space) of CMEs which minimizes the projection effects for full halo CMEs. The plane of the sky values can deviate from the real radial speed of the CME front, depending on the actual direction of the motion. They consider only full halo (FH) CMEs (width 360°). Their sample includes CMEs of wider range of initial velocities. To improve prediction, they introduce the effective acceleration from two groups of CMEs which do not have acceleration cessation at any place between the Sun and Earth. Further the acceleration cessation distance is dependent on the initial velocity of a given event.

The new linear relation connecting acceleration with initial velocity of CMEs is

$$a_3 = 4.11 - 0.0063u \tag{4}$$

Clearly the coefficients of this relation differ from those of Eqs. (1) and (2) because the relation (4) depends on a data set which includes several fast CMEs.

Another linear relation which is based on the assumption that CMEs do not stop accelerating at any place between the Sun and Earth, reads as follows:

$$a_4 = 3.35 - 0.0074u \tag{5}$$

But the relation

$$a_5 = 2.99 - 0.0067u \tag{6}$$

leads to better travel times when uncorrected initial velocities ''u'' are used (Michalek et al., 2004).

Using this method they were able to predict the arrival times of HCMEs with an average error of 8.7 h and 11.2 h for space and projected initial velocities, respectively. They conclude that each population of CMEs may need a separate acceleration profile for an accurate prediction in which the average effective acceleration depends only on the initial velocity.

Owens and Cargill (2004) analyse the causes of errors in arrival times of CMEs at 1-AU in the models, namely constant acceleration/deceleration model of Gopalswamy et al. (2000), cessation of acceleration before 1-AU model of Gopalswamy et al. (2001) and aerodynamic model of Vrsnak and Gopalswamy (2002). They discuss possible sources of error and possibilities of improvements.

Taking above approaches into consideration, we consider it worthwhile to determine the arrival times of CMEs at Earth taking a larger database. In the next section (Section 2) we present data set used, and in Section 3 we present our model and obtained results. Section 4 describes about location of HCMEs and Section 5 describes about the speed of HCMEs. In Section 6 we discuss our result. The last section (Section 7) contains our conclusions.

2. Data

The data used in this study include only full Halo CMEs that occurred between 1996 and 2007 and hit the Earth. We use LASCO data for studying the solar origins of the CMEs. The data for CMEs have been taken from the catalogue maintained by the Centre for Solar Physics and Space Weather (CSPSW) (http://cdaw.gsfc.nasa.gov/CME_list) and other data were taken from Gopalswamy et al. (2001), Michalek et al. (2004), Manoharan et al. (2004) and Gopalswamy et al. (2007). The Large Angle Spectroscopic Coronagraph (LASCO) imaging instrument on board SOHO (Brueckner et al., 1995) currently has two functioning coronagraphs, C2 which has a field of view (FOV) of 1.5–6 R_S and a cadence of around 30 min, and C3 with a FOV of 3.7–30 R_S and cadence of around 50 min. The C1 telescope that can observe CMEs closer to the Sun was disabled in June 1998. It may be remarked that there is a data gap during the period July– September 1998, because during this period SOHO satellite became inoperational (Gopalswamy et al., 2009; Mittal et al., 2009b).

Since the major cause of the space weather disturbances is Earth directed full HCMEs, so we have taken only Earth directed full HCMEs in our study. All the Earth directed HCMEs have been taken from Gopalswamy et al. (2007).

For each event the catalogue contains height-time plots, plane of sky speeds and the corresponding accelerations. The CME speed is determined from both the linear and the quadratic fits to the height-time measurements. In our study we analyse the linear (constant speed) fit which is preferable for 90% of the CMEs (Mittal et al., 2009a).

The definition of full or partial halo is based on the azimuthal extent of CMEs in the LASCO field of view (Webb et al., 2000). The data of type II radio burst (frequency range 1–14 MHz) are taken from WIND/WAVES catalogue and the data of solar flares (>X1) are taken from GOES.

The observed arrival time is marked by the time at which the D_{ST} index becomes minimum.

3. Model and results

In this section we have discussed arrival time of HCMEs. We have grouped the halo CMEs in different categories. In first we have taken all the Earth directed HCMEs and created three groups. Firstly we have studied all the Earth directed HCMEs and than CMEs having speed >500 km/s and CMEs having speed <500 km/s. We have also studied that whether HCMEs are associated with type II radio burst, X-class flares or with both radio bursts and X-class solar flares