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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. For the forecasting of Space Weather, It is necessary to predict the CMEs arrival time at 1 AU. Here we have tried to predict the arrival times as accurately as possible of Full halo CMEs only.

Key words: Sun, Coronal mass ejections, ICMEs, Arrival time

1 Introduction

Coronal mass ejections are a topic of extensive study, since they were first detected by NASA's OSO-7 space craft (Tousey, 1973). When huge magnetized plasma erupts and travels through the solar corona is termed as coronal mass ejections (CME). CMEs may have three characteristic structures (the forefrontal structure, or leading edge, the dark cavity region, and the bright core, or filament) (Illing & Hundhausen, 1985). 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, Wu et al., 2011). CMEs originating close to the central meridian of the Sun directed towards the earth are the most geoeffective 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 & 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 (like magnetic flux; current sheath, shocks etc) 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, Mittal and Narain, 2010).

Combining CME observations made by SOHO/LASCO and interplanetary CMEs (ICMEs) (which are responsible for geomagnetic storms) measurements near the Earth, Gopalswamy et al. (2001) developed an empirical model to predict the 1-AU arrival time of CMEs. 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:

$$a_1 = 1.41 - 0.0035u \qquad (1)$$

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

$$a_2 = 2.193 - 0.0054u \qquad (2)$$

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,

$$S = ut + \frac{1}{2}at^2 \qquad (3)$$

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 10.7h.

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 360^0). 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

$$a_3 = 4.11 - 0.0063u \qquad (4)$$

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:

$$a_4 = 3.35 – 0.0074u \qquad (5)$$

But the relation

$$a_5 = 2.99 – 0.0067u \qquad (6)$$

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 8.7h and 11.2h 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) analyze 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 arrival times of CMEs at Earth taking a larger data base. In the next sections, we present our model, data set used and obtained results. The last section contains discussion and 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). The Large Angle Spectroscopic Coronagraph (LASCO) imaging instrument on board SOHO (Brueckner et al. 1995). LASCO currently has two functioning coronagraphs, C2 which has a field of view (FOV) of 1.5–6 Rs and a cadence of around 30 minutes, and C3 with a FOV of 3.7–30 Rs and cadence of around 50 minutes. The C1 telescope which 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).

Since the major cause of the space weather disturbances are Earth directed full HCMEs, so we have taken only Earth directed full HCMEs in our study. All the Earth directed HCMEs has been taken from Gopalswamy et al. (2007) and Richardson & Cane (2010).

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. The speed of CME is usually measured by constructing a time–height diagram for the fastest moving feature of the CME front as it appears projected on the plane of the sky. 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. In our study we analyze the linear (constant speed) fit which is preferable for 90% of the CMEs (Mittal et al., 2009).

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 observed arrival time is marked by the time at which the D_{ST} index is minimum and ICME event occurs.

3. Model and Results

We have selected total 96 events from the data set reported by Gopalswamy et al. (2007), Richardson & Cane (2010) and also from SOHO/LASCO catalogue (http://cdaw.gsfc.nasa.gov/CME_list). We have calculated acceleration by the relation v = u+at, as by Gopalswamy et al. (2000 and 2001). The definite correlation between the effective acceleration (a) and initial speed (u) which is given below:

$$a = 2.193 - 0.0032u \qquad (7)$$

This relation is used in the kinematics equation, $S = ut + \frac{1}{2}at^2$ following Gopalswamy et al. (2000 and 2001) and we get the calculated travel time for the CMEs.

We used CMEs Linear Speed, 2nd-order Speed at final height and 2nd-order Speed at 20 Rs and we find correlation between observed and calculated travel time on the basis of speeds respectively.

There is high correlation (r = 0.79) between calculated and observed travel time for 2nd-order Speed at 20 Rs, while correlation between observed and calculated travel time for Linear Speed, 2nd-order Speed at final height are 0.68 and 0.69 respectively.

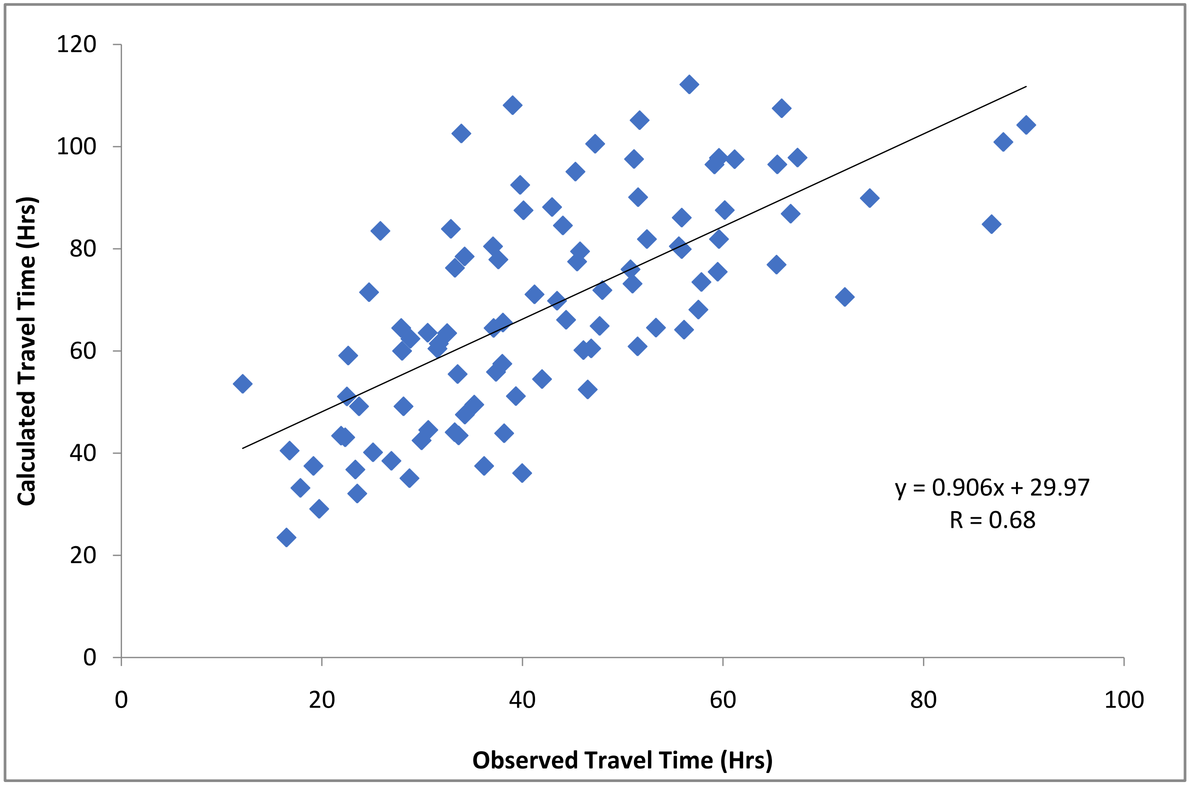

Fig 1: Shows linear relation between observed travel time and calculated travel time for 96 HCMEs have CMEs Linear Speed.

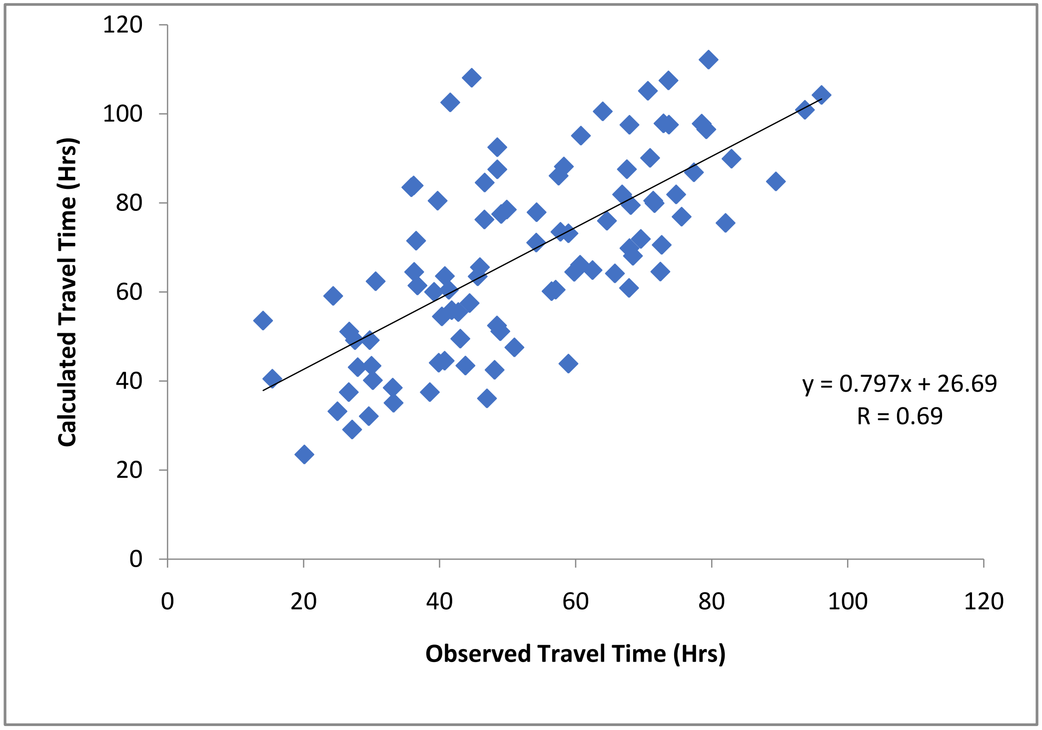

Fig 2: Shows linear relation between observed travel time and calculated travel time for 96 HCMEs have CMEs 2nd-order Speed at final height.

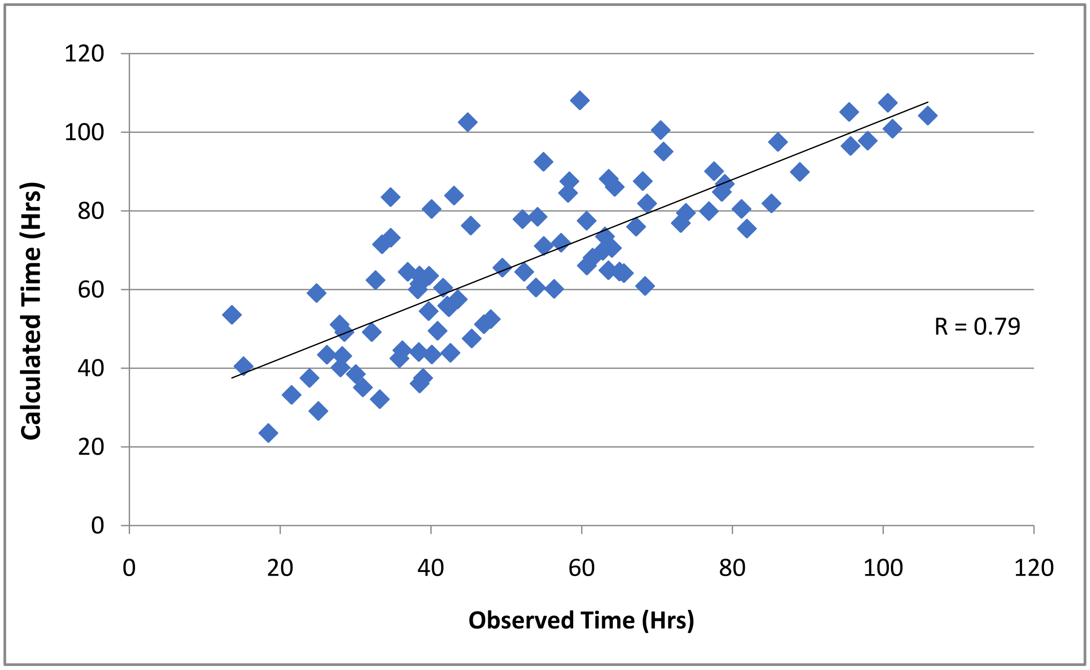

Fig 3: Shows linear relation between observed travel time and calculated travel time for 96 HCMEs have CMEs 2nd-order Speed at 20 Rs.

4. Discussion and Conclusion:

In their study Gopalswamy et al. (2000) study the 28 IP (interplanetary) events associated with CMEs and give an empirical model which works much better for fast CMEs in compare to slow CMEs.

In 2001, Gopalswamy et al., again describe an empirical model to predict the arrival time of CMEs at 1AU by the selection of 47 ICME events. Their model predicts the arrival time with the error 15.4 to 10.7 Hrs. This model is also in good agreement with high speed CMEs.

In 2003, Michałek et al., studied the arrival time of Halo CMEs for 83 events. In their study Michałek et al. predicted the arrival time of HCMEs with an average error of 8.7 and 11.2 Hrs for space and projected initial velocities, respectively.

Our main aim has been to predict the arrival times of HCMEs in the vicinity of the Earth as correctly as possible.

Figure 1 exhibits relation between arrivals times (in hours) of CMEs (thick line) calculated as a function their linear speed (in km/s) and observed arrivals times (in hours). The correlation coefficient is 0.68. It is clear that discrepancies between observed and calculated times are quite significant.

In Figure 2 we exhibit relation between arrivals times (in hours) of CMEs calculated as a function their 2nd-order Speed at final height (in km/s) and observed arrivals times (in hours). The correlation coefficient is 0.69.

Figure 3 shows the relation between arrivals times (in hours) of CMEs calculated as a function their 2nd-order Speed at 20 Rs (in km/s) and observed arrivals times (in hours). The correlation coefficient is 0.79.

Table 1 compares arrival times at different CME speeds.

Owens and Cargill (2004) have discussed predictions of the arrival times of CMEs at 1-AU. They found that projection effects are not the major cause of the error in the arrival times. They also find that there is a weak trend towards early arrival for stronger magnetic field strength ICMEs. Further the late arriving ICMEs have both thicker sheath regions and lower magnetic field intensities. They conjecture that the primary cause of error in arrival times is most likely a geometrical effect which can arise for two reasons. First, from a single in situ observation of ICMEs, one does not know which part of the event one is sampling. Since an ICME is a curved 3-D structure and the measured arrival time will depend on which part of the ICME is being sampled. Second, ICMEs become deformed in the interplanetary medium, with an elongation taking place in a direction perpendicular to the principal direction of the motion. Hence STEREO mission observations can give a better determination of the velocity vector of the CME at the Sun.

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