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Empirical CME-SSC listing model

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Abstract- The association listing of Coronal Mass Ejection-Storm Sudden Commencement (CME-SSC) events is the aim of this research. Certain criteria have been put to select the CME-SSC pair events automatically. The travel time of the CME shock could be estimated from an empirical equation that depends on spatial, temporal, CME angular width and projection effect conditions. A high correlation was found according to a certain algorithm between the initial speed and the travel time of the CME shock, R=0.81 with mean arrival time error 16.67 hours for 269 events during the period 1996-2010.

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1. INTRODUCTION

CMEs are known to be the major cause of severe geomagnetic disturbances, often referred to as space weather. These CMEs can affect Earth's magnetospheric environment and technological systems [Gopalswamy *et al.* (2001)]. The strongest geomagnetic disturbances are caused by CMEs traveling towards Earth. In view of the possible deleterious effects of space weather on space and ground-based technical systems (e.g. spacecraft charging, lowering of orbit, communication interruptions, flow of induced currents along transmission lines), making a prediction of the arrival time of a CME at 1AU, and its properties at that time, is highly desirable [Owens and Cargill (2004)].

Geomagnetic storms are caused mainly by solar wind transients from the coronal mass ejections (CMEs) and solar flares or by the co-rotating interaction regions (CIRs) formed during the interaction between the high and low speed streams. The majority of storms begin with a sudden impulse which signals the arrival of solar plasma. During this time, the geomagnetic field intensity is increased, the storm-time H component being positive. Such sudden impulses preceding geomagnetic storms are called storm sudden commencements; SSC [Mansilla (2014)]. The present generation of forecasting models all predict the travel time of a CME to 1AU. This time is defined as being the time between the first observation of the CME by a coronagraph, and the arrival of the leading edge of the ICME at 1AU [Owens and Cargill (2004)].

According to McKenna-Lawlor et al. (2002), the arrival times at the Earth of eleven flare associated halo CMEs generated shocks, for the period (1997-2001), were forecasted based on "real-time" data using three numerical models, namely the Shock Time of Arrival Model (STOA), the Interplanetary Shock Propagation Model (ISPM) and the Hakamada-Akasofu-Fry Solar Wind Model (HAFv.2). These predictions are compared with the measured arrival times. The models are all generally successful in predicting shock arrivals. STOA scored the smallest values of "predicted minus observed" arrival times (typical precision better than 8 h). The ratio of the calculated standard deviation of the transit times to Earth to the standard deviation of the measurements was estimated (treating interacting events as composite shocks) for each model and these ratios turned out to be 0.60, 1.15 and 1.02 for STOA, ISPM and HAFv.2, respectively.

Gopalswamy et al. (2000 &2001) and Michałek (2004) developed an empirical model to predict 1-AU arrival time of the CMEs. Gopalswamy et al. (2000) model could not account for the observation that CMEs with a slow initial speed (U <500 km/s) have an approximately constant travel time of 4.2 days. So a modification has been done for that model by assuming that ICME acceleration ceased at a heliocentric distance of 0.76 AU (d1) for all CMEs (found to be the best fit), regardless of their initial speed, so the total travel time of the CME from the sun to 1 AU is the sum of the travel time to d1 at constant acceleration, and the travel time taken from d1 to 1AU: (d2=1AU-d1) at constant

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speed [Gopalswamy et al. (2001)]. Their model was based on the fact that the speed distribution of ICMEs, detected by the Wind spacecraft was much narrower in the range (300–1000) km/sin comparison to the velocity distribution of CMEs observed by SOHO/LASCO near the sun (100–2000) km/s. CMEs are ejected and accelerated by the magnetic field of the corona in the interplanetary space according to their relative velocities with the solar wind. ICMEs are depending on their speed relative to the solar wind, either accelerated or decelerated towards the solar wind speed. Fast CMEs are decelerated mostly by the solar wind due to friction which is proportional to the square of the velocity difference [Michalek et al. (2004)]. Gopalswamy et al. (2001) worked upon 47 events through the period (1996-2000) and obtained a mean time error about 10.7 hours.

To be confident that a CME and ICME are manifestations of the same ejection from the sun (and are not subject to strong interaction with other ejecta), it is required that an observation of a single halo CME be followed 1 to 5 days later by a clear ICME signature in the magnetic and plasma data at 1AU. However, such ideal situations are quite rare around Solar Maximum, Hence, Owens and Cargill (2004) relaxed the selection criteria in order to have enough CME-ICME pairs for comparison with models,

Richardson and Cane (2008) introduced a list of near-Earth interplanetary coronal mass ejections, which are believed to be the interplanetary manifestations of the coronal mass ejections seen near the sun by coronagraphs. They studied the effects of ICMEs on energetic particles, including those accelerated by solar flares, interplanetary shocks, and galactic cosmic rays, during 1996-2002.To examine these effects; it is needed to know when ICMEs are passing the observing spacecraft. Conversely, energetic particle observations can help to indicate when ICMEs are present. Some two dozen in-situ signatures of ICMEs (earlier terms include "shock drivers", "pistons", "ejecta") have been reported in magnetic field, plasma, solar wind composition and charge states as well as energetic particles from super thermal solar wind to galactic cosmic ray energies [Zurbuchen and Richardson (2006)]. Thus, ideally ICME identification should combine as many data sets as possible, such as those available from ACE and other near-Earth space crafts.

2. Approach

The aim of this work is to create an empirical model to determine the travel time according to CME shock speed during a wide period 1996-2010, instead of the small number of events used in constructing the previous models.

We ignored stealth CMEs and cases when two CMEs merged or interacted [Lugaz *et al.* (2012)] because of the difficulty of their consideration into our current work. This will be achieved in a future work.

In addition, the speed of CMEs must be corrected from projection effect as follows:

CME Angular Width

All CME events data having the angular width greater than 180° (of course including Halos) are ignored in order to minimize the error of the CME's angular width calculation. Since the angular width of Halo CME is not known, thus using any empirical relation for the projection effect of the CME speed leads to large uncertainties [Michalek *et al.* (2008)]. In addition, the non-halo CMEs can also reach Earth especially CMEs ejected from the left side of the solar disk due to the clockwise solar rotation [Mawad and Shaltout (2011)]. According to the modified CME-ICME list of Richardson and Cane, the number of halo and non-halo CMEs which reached the Earth during the period (1996-2010) was 94 and 67 respectively.

Gopalswamy et al. (2001) found that the predicted arrival times have a better agreement with the observed arrival times when no projection correction applied to the SOHO CME measurements. However, we will take projection effect into our consideration.

Based on an earlier work by Sheeley *et al.* (1999), Leblanc *et al.* (2001) attempted to correct the measured plane-of-sky speed of the CME using the known longitude λ and latitude β of the eruptive region using the relation:

$$V_{rad} = V_{sky}\,(1 + \sin\phi)/(\sin\phi + \sin\alpha) \qquad (1)$$

Where, V_{rad} and V_{sky} are the space (radial speed) and the plane-of-sky speeds, respectively, αis the actual half-angular width of the CME, and ϕ is the heliocentric angle of the central axis of the CME which is given by$\cos\phi = \cos\lambda\cos\beta$, where λ and β are the corresponding longitude and latitude of the eruptive region, respectively.

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In the case of CME events, we have no latitude and longitude observations, the origins of CMEs are hidden by artificial eclipse of LASCO coronagraphs. That is why our CME events selection is restricted to the CMEs ejection from the active regions only, in order to be able to determine its location. This problem is solved by assuming the CME locations (latitude and longitude) to be roughly that of solar flares. The locations of solar flares as origins of CMEs have been listed by temporary and spatial conditions as follows:

Temporal Condition

In earlier studies on the correlation between solar flares and CMEs, Shaltout et al. (2006) have put the criteria that the CME ejection time should be within the start and end times of the solar flare (F_{start}<CME_t< F_{end}), where CME_t is the CME ejection time, F_{start} is the solar flare start time and F_{end} is the solar flare end time.

On applying this assumption, we have obtained a limited number of flare-CME associated events. In the current study, the association of solar flares with CMEs is not our main purpose; we just need to locate the CME to an active region. However, a solar flare decays rapidly, its active region remains for several days. We assumed that the solar flare location is the same as the active region location. We thus modified our selection rule to become that of the nearby solar flare that occurs through the same day of the CME event.

There could be tens of flares in the same day, so this modification will be restricted by the spatial condition as follows:

Spatial Condition

Vršnak et al. (2005) used the condition $|\Psi_{CME} – \Psi_F| < \Phi/4$ where Ψ_{CME} is the position angle of CME (obtained from CME catalogue), Ψ_F is the position angle of the solar flare and Φ is the angular width of CME (i.e. the location of the flare or filament is bounded by quarter of the CME width). Mahrous et al. (2009a) modified this condition to become $|\Psi_{CME} – \Psi_F| < \Phi/2$ (i.e. the location of the flare is bounded by half of CME width), the position angle Ψ_F can be estimated from latitude β and longitude λ (obtained from NOAA) by formula $\Psi_F=\text{Tan}^{-1}[\sin \lambda / \tan \beta]$.

Estimation of Travel and Error Times

We listed the nearby SSC to calculate travel time T_C of CMEs shocks. Then, we postulate that the ICME shock signature upon the Earth's magnetosphere is the sudden storm commencement (SSC), and then the actual travel time of the CME shock ends with a corresponding defined SSC signal enhancement.

The primarily travel time, T_C, can be estimated for CMEs which caused the SSC (U is CME speed) as follows:

$$T_C=(1\ \text{AU})/U \qquad (2)$$

In addition, we checked and confirmed CME-SSC association manually and listed them, since it is impossible for the CMEs to reach the Earth's magnetosphere with a linear speed. In addition, the distance that is traveled by CMEs is greater than 1 AU. So we just applied this assumption in order to guide us for the manual selection.

Therefore, we can select SSC correctly by calculating the minimum error time according to:

$$T_{Error} = \text{Min}\{|T_C-T_{SSC}|\} \qquad (3)$$

Where, T_{SSC} is the actual arrival time of ICME shock impacted the magnetosphere and caused a corresponding SSC, and T_{Error} is the error of arrival time calculation. The actual arrival time is the SSC time, while, the calculated travel time is estimated from initial speed of CME by using power-fitting formula of our CME-SSC list.

We restricted the CME-SSC association by the following conditions:

1. Error time T_{Error}< 36 hours.
2. $T_{Min}<(T_{SSC}-T_{CME})<T_{Max}$ (4)

Where, T_{CME} is the ejection time of CME, T_{Min} and T_{Max} are minimum and maximum travel times as the boundary conditions chosen according to our model which are $T_{Min}\approx 1$ day, and $T_{Max}\approx 7$ days [Shaltout and Mawad (2010)]. This is an extension for T_{Max} value, five days, which was used earlier [Owensand Cargill (2004)].

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3. Data Sources

We have used the solar wind data of OMNI satellite obtained from NOAA with 5 minutes resolution data during the period 1996-2010, obtained from URL [http://cdaweb.gsfc.nasa.gov/istp_public/].CMEs data were taken from SOHO LASCO CME Catalog,15877 CMEs events, during the period 1996-2010 were obtained from URL [http://cdaw.gsfc.nasa.gov/CME_list/]. We have used the solar flares data from NOAA data center; we have 24572 flare events during the same period. The geomagnetic sudden storm commencements SSC were taken from NOAA satellite (381 SSC events).

The CME-ICME list produced by Richardson and Cane is obtained from the following URL: [http://www.srl.caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm].

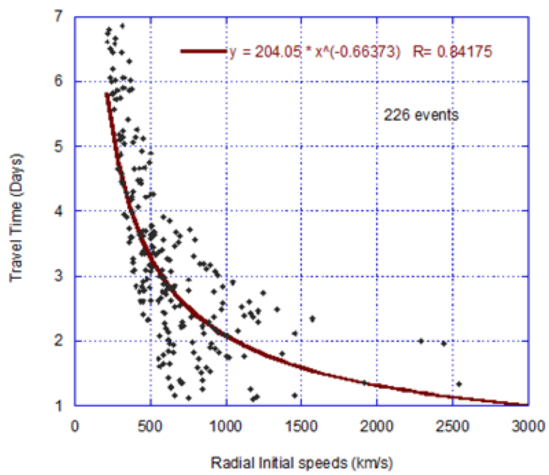

Fig. 1. The corrected CMEs initial speeds in relation to their actual arrival time.

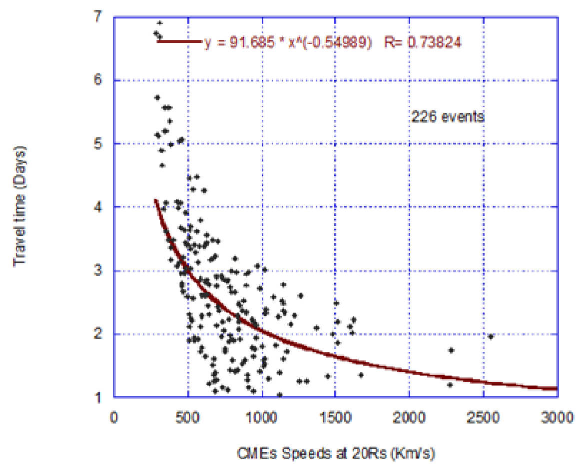

Fig. 2. The corrected CMEs speeds at 20R⊙in relation to their actual arrival time.

4. Results and Discussion

We have performed a list that includes the SSC corresponding to the CME events which represents the ICME shock arrival time. We have applied the algorithm to list it programmatically as a simulation to our criteria and condition for manual selections.

We have plotted the relation between the initial speed and the actual arrival time of CME events which are associated with SSCs depending on power fitting as shown in figure (1). High correlation between the initial speed and travel time of the CME shock is found, R~0.84 for 226 events during solar cycle 23.

We have plotted the relation between the speed at 20R⊙ and the actual arrival time of CME events which are associated with SSCs as shown in figure (2). The correlation between the speed at 20R⊙ and travel time of the CME shock decreased to R~0.74 for 226 events during solar cycle 23.

Because of the higher correlation coefficient (R~84%), we have preferred to use the CME initial speeds than CMEs speeds at 20R⊙ (R~74%). This result is compatible with previous results. Figures (1) and (2) show that the travel time of CME shock can be predicted better with low CME speeds more than CMEs which have high speeds, because the points are crowded around the fitting line for speeds <500Km/s and are scattered for high speeds >500Km/s.

In this study, the CMEs initial speeds are used after applying the projection effect, which gives good results. On the other hand, Gopalswamy et al. (2001) have noted that the prediction of 1AU arrival times of CMEs based on their initial plane-of-sky speed is much better than those with projection correction.

The power equation fitting that describes the relation between the CME's initial speed and its actual travel time can be described by the following power equation:

$$T = 204.05 \times V_{initial}^{(-0.66373)} \quad (5)$$

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Where $V_{initial}$ is the CME's corrected initial speed in km/s, and T is the travel time of shocks in days.

Formula (5) is used to estimate the CME-SSC pair events automatically; the travel time is computed using the initial speed of CMEs listed in the SOHO/LASCO catalogue after correction for projection effect. Thereafter, we compared the computed arrival time with the nearest SSC (the actual arrival time) depending on the relation (5) deduced from figure (1). We found that there is a strong correlation coefficient between travel times and the corrected initial speeds with R ~ 0.81and mean arrival time error about 16.67 hours for 269 selected events as shown in the figure (3).

The correlation coefficient may increase on using the actual origin location of the CME, but it is not available. However, we approximated this origin location by using the longitude and latitude of the associated flares, as described earlier.

Gopalswamy et al. (2001) model depends on Newton's second law, although it is not applicable to plasma motion, which results in the predicted travel time increases as the CME speed increases for low CME's speeds (smaller than about 500 km/s), while for high CME's speeds (greater than about 500 km/s) the predicted travel time decreases as CME speed increases.

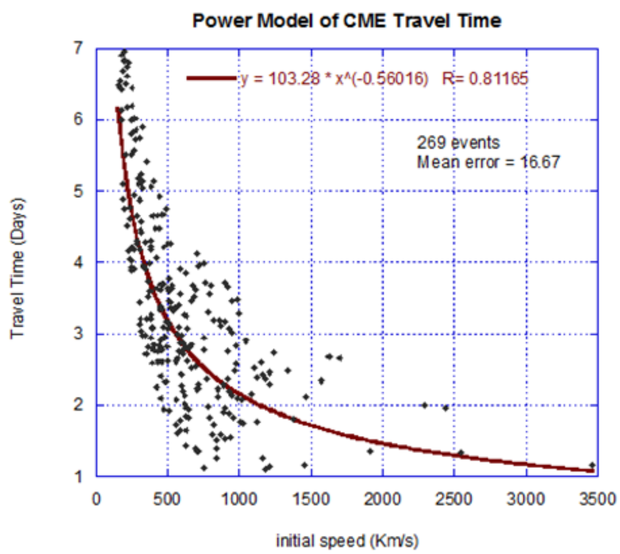

Fig. 3.A prediction curve of CME arrival time.

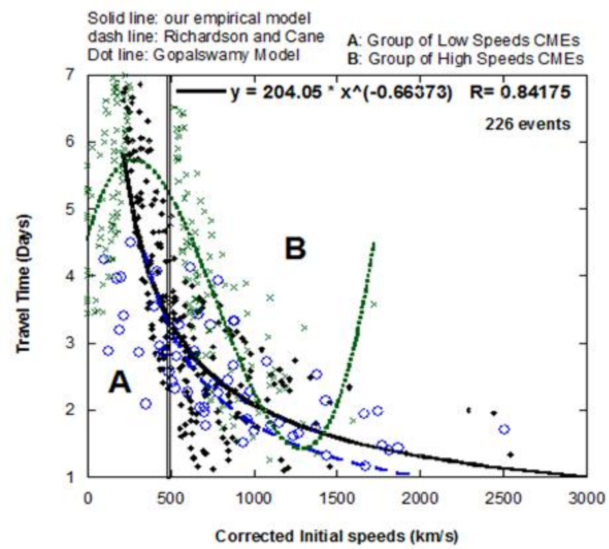

Fig. 4. Our prediction modeling comparison with *Gopalswamy* and *Richardson and Cane* models.

Mahrous et al. (2009b) improved the accuracy of the predicted arrival time; they divided the CME events into two groups according to their effective acceleration and deceleration. Their model works well for events with a negative acceleration for initial velocities between 500 and 2500 km/s. The model introduced by Gopalswamy is better for events with initial velocities near the solar wind velocity. The group of low speed CMEs obtained by Gopalswamy *et al.* (2001) shown in figure (4) is different from Richardson and Cane (2008).

The prediction curve presented by Richardson and Cane (2008) shown in figure (4) is obtained by power fitting of their CME-ICME list.

The Gopalswamy's prediction curve is obtained by power fitting for CME-ICME list introduced in his model depending on empirical relation and Newton's law [Gopalswamy *et al.* (2001)].

The group of high-speed CMEs of our model is compatible with Richardson and Cane (2008), Gopalswamy (2001) and *Mahrous et al.* (2009b), while the group of low CMEs speed differs from Gopalswamy (2001) but is still compatible with Richardson and Cane (2008) and Mahrous et al. (2009b).

It is obvious from this figure that our model coincides with Richardson and Cane (2008) for low CME speeds while slowly differs from it for high CME speeds. The difference increases with the increase of CME speeds. The reason

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for this trend is that our model depends on SSC (arrival time of CME shock), while Richardson and Cane have depended on the arrival time of ICME in their work.

In the following figure (5), the CMEs travel times are distributed between one day and 7 days with the maximum number of events reaching within about 2-3 days depending on their initial speeds.

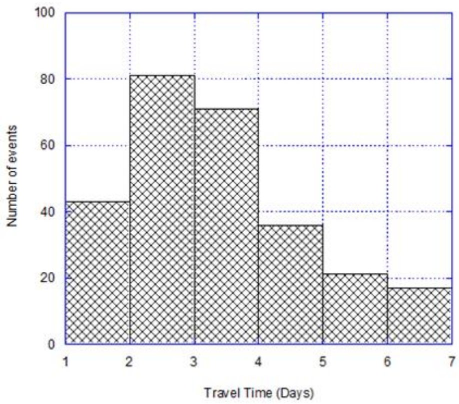

Fig. 5. CME travel time histogram.

The mean time error in this study approaches 16 hours for 269 listed events during 1996-2010. The wide range of the period selected for this work has a contribution to the large error time, but this error time is limited to 36 hours as was introduced by [Gopalswamy *et al.* (2001)], with the maximum number of events around 6-9 hours. This result may be attributed to the good efficiency of our work for estimating large number of events according to our CME-SSC listing model, since as the number of events under scope increases, the calculated error time increases logically. Also, the wide range of the estimated time error is a reflection of the wide range of the CMEs travel time (1-7 days).

5. CONCLUSION

We have developed a list of CME-SSC association list with the purpose of constructing an empirical model for CMEs travel time. We have used CME data obtained from SOHO/LASCO CME Catalog (15877 events) and SSC (381 events) from NOAA, during the period 1996-2010. Some of previous studies created lists manually according to some criteria and conditions, and others created numerical models but according to small number of events.

We corrected the CME speed for projection effect. In addition, we estimated the error in travel time and compared it with previous studies.

We found that the travel time of CME shock can be estimated from CME corrected initial speed as follows:

$$T = 204.05 \times V_{initial}^{(-0.66373)}$$

Where $V_{initial}$ is the initial speed in km/s, and T is the travel time in days. This empirical equation gives high correlation coefficient R=0.84.

The direction of the interplanetary magnetic sector may affect the travel time of the CME.

The CME initial speed gives accurate travel time than CME speed at $20R_{\odot}$. In addition, the corrected initial speed for projection effect gives more accurate travel time than none corrected speeds. The mean time error has been examined in this study. It is found to approach 16 hours for 269 listed events during 1996-2010.

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