# Effect of Solar Wind Convection on CME Transit Time Postprint

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## Abstract

Based on the empirical model for forecasting Coronal Mass Ejection (CME) transit time proposed by Gopalswamy et al. [2001], we selected 52 CME events related to geomagnetic effects with Dst<-50nT and 10 CME events causing intense geomagnetic storms (Dst<-200nT) during 1996-2007, and combined with solar wind observation data from the ACE satellite at 1 AU, we analyzed the influence of background solar wind convection effects on the forecast of CME transit time to 1 AU. For the 52 CME events, after considering the influence of solar wind convection effects, the forecast standard deviation decreased from 16.5 hours to 11.4 hours, the corrected error distribution tended toward a Gaussian distribution, and the forecast error for 68% of events was less than 15 hours; for the 10 CME events causing intense geomagnetic storms, after considering the influence of solar wind convection effects, the forecast standard deviation decreased from 10.6 hours to 6.5 hours, and the forecast error for 6 of these events was less than 5 hours. The research results indicate that, for CME events, considering the influence of background solar wind convection effects can reduce the standard deviation of forecasting CME transit time, demonstrating the importance of solar wind convection effects for forecasting CME transit time.

## Full Text

## Influence of Solar Wind Convection Effects on CME Transit Time

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## Abstract

Based on the empirical model for forecasting coronal mass ejection (CME) transit time proposed by Gopalswamy et al. [2001], we selected 52 CME events associated with geomagnetic effects (Dst $< -50$ nT) and 10 CME events causing major geomagnetic storms (Dst $< -200$ nT) during 1996–2007. Using ACE satellite observations of interplanetary solar wind at 1 AU, we analyzed the influence of background solar wind convection effects on predictions of CME arrival time at 1 AU. For the 52 CME events, incorporating the influence of solar wind convection effects reduced the standard deviation of predictions from 16.5 hours to 11.4 hours. The corrected error distribution approached a Gaussian distribution, with prediction errors for 68% of events falling below 15 hours. For the 10 major geomagnetic storm events, considering solar wind convection effects decreased the standard deviation from 10.6 hours to 6.5 hours, with six events exhibiting prediction errors of less than 5 hours. These results demonstrate that accounting for background solar wind convection effects reduces the standard deviation of CME transit time forecasts, highlighting the importance of solar wind convection effects for predicting CME arrival times.

**Keywords:** coronal mass ejection, geomagnetic storm, ambient solar wind speed

In the vast cosmos, the Sun is the star most intimately connected with humanity. It provides various forms of energy for life on Earth, bringing light and warmth. However, violent eruptive activities on the Sun—such as sunspots, prominence eruptions, solar flares, and coronal mass ejections—release enormous amounts of energy in short periods, ejecting large quantities of magnetized plasma, high-energy particles, and enhanced electromagnetic radiation into interplanetary space. These phenomena trigger X-ray bursts, particle storms, and are colloquially termed "solar storms." When solar storms reach Earth, they typically produce severe space weather changes in the geospace environment, triggering various geophysical effects such as magnetic storms, substorms, and ionospheric storms. These can cause operational failures or even complete collapse of space-based and ground-based technical systems including satellites, communications, navigation, and power transmission, resulting in substantial economic losses and potential threats to human safety. Consequently, hazardous space weather events triggered by solar storms represent a key focus of space weather research [1].

A geomagnetic storm is a violent disturbance of Earth' s entire magnetosphere. At mid- and low-latitude stations, a significant decrease in the horizontal component of Earth' s magnetic field is frequently observed, lasting for several days—this phenomenon is called a geomagnetic storm. The intensity of geomagnetic storms is measured by the Dst index (in units of nT), which is derived by averaging hourly measurements of the horizontal component from four mid- to low-latitude geomagnetic stations and taking the difference from quiet-day hourly averages. Currently, magnetic storms are classified into four categories based on Dst values: weak storms ($-50$ nT < Dst < $-30$ nT), moderate storms ($-100$ nT < Dst < $-50$ nT), intense storms ($-200$ nT < Dst < $-100$ nT), and major storms (Dst < $-200$ nT) [1].

Coronal mass ejections (CMEs) refer to large-scale plasma structures ejected from the Sun and propagating through interplanetary space, representing the most important weather process in the solar atmosphere. Their interplanetary counterparts are called interplanetary coronal mass ejections (ICMEs) [1]. Earth-directed CME/ICME events are typically associated with large geomagnetic storms, interplanetary shocks, and high-energy particle events, often producing strong geophysical effects and representing a primary factor in hazardous space weather. Therefore, research on CMEs has received increasing attention, with CME arrival time at Earth being a crucial parameter in space weather forecasting.

Since observational data are concentrated near the Sun and near Earth, with insufficient interplanetary space observations, combined with the complexity, dynamic nature, temporal variability, and coupling of the Sun-Earth system, as well as limited understanding of CME propagation characteristics in interplanetary space, accurate prediction of CME arrival time remains challenging. CME transit time forecasting methods generally fall into two categories: empirical statistical models and physics-based propagation models. Both approaches have advantages and disadvantages, with no significant difference in forecasting effectiveness. However, operational forecasting requirements demand both reliability and speed, making empirical statistical methods the common choice for predicting CME transit time.

Statistical forecasting methods typically analyze correlations between CME transit time and near-Sun observational characteristics based on a certain number of CME sample events, yielding empirical forecasting relationships for arrival time. The most commonly used near-Sun parameter is CME initial speed. Numerous studies have developed various CME transit time forecasting models based on initial speed using different event samples, including internationally representative works by Srivastava et al. [2-3] (using 64 events), Gopalswamy et al. [4-6] (using 47 events), and Wang et al. [7-9] (using 15 events). Although these models differ in form, they share similar advantages and disadvantages in forecasting performance, with standard deviations all exceeding 10 hours [2-18]. Such large forecasting errors cannot meet practical forecasting needs. Therefore, improving statistical forecasts of interplanetary disturbance arrival times caused by CMEs warrants serious attention.

One factor limiting the effectiveness of statistical forecasting models is that they consider only the influence of CME initial speed on transit time. In reality, numerous complex factors affect CME transit time, and relying solely on initial speed inevitably limits forecasting accuracy. To address this, we propose a new concept of "commonality"and "individuality"in space weather forecasting. Based on 52 CME events during 1996–2007 and 10 CME events causing major geomagnetic storms, combined with solar wind observations at 1 AU from spacecraft, we analyzed the influence of convection effects in fast and slow background solar wind on predictions of CME arrival time at 1 AU.

## 1 A New Concept of "Commonality" and "Individuality" in Space Weather Forecasting

Statistical forecasting models for CME transit time represent optimal fitting relationships between initial speeds of numerous CME events and observed arrival times of corresponding ICME disturbances at Earth. These models reflect average propagation characteristics of many CME/ICME events through the Sun-Earth interplanetary space, which can be termed the "commonality" of numerous CME/ICME events. The scatter of each specific event from the fitted curve results from various physical factors of that event, representing the "individuality" of that particular CME/ICME event. Clearly, a close relationship exists between the statistical "commonality" and each event' s "individuality." If this relationship can be interpreted through observational and physical analysis of each specific event, the qualitative forecast obtained from statistical models can be corrected to yield more realistic predictions. In other words, combining the "individuality" of specific space weather events with the "commonality" of statistical forecasts—injecting important physical correction factors contained in "individuality" into the "commonality" of statistical forecasts—enables quick corrections to statistical predictions through observational and theoretical identification of correlation functions between "commonality" and "individuality," thereby improving current statistical forecasting capabilities for hazardous space weather events.

Several important physical factors affecting CME transit time include: (1) convection effects of ICME propagation in fast versus slow background solar wind; (2) CME energy and its release mechanism—impulsive versus piston-driven; (3) three-dimensional anisotropic flow of interplanetary solar wind; and (4) interplanetary magnetic field—open versus closed field configurations.

This paper primarily investigates convection effects of interplanetary disturbances propagating in fast and slow background solar wind based on multi-spacecraft observations, examining their influence on disturbance arrival time predictions. We assume that background solar wind speed remains constant during CME propagation, with its value defined as the average of quiet solar wind speeds observed by the ACE spacecraft during the 12-hour period before ICME arrival at Earth.

## 2 Statistical Forecast Model—Uniform Acceleration/Uniform Velocity Model

To explore the relationship between "commonality" and "individuality" in space weather event forecasting, we selected an empirical statistical model as the "commonality" for studying CME events. After analyzing current internationally representative forecasting models, we chose the uniform acceleration/uniform velocity model presented by Gopalswamy et al. [4-5].

Gopalswamy et al. [4-5] studied the kinematic characteristics of CME events in SOHO/LASCO and the local plasma characteristics of corresponding ICMEs near Earth, proposing an empirical model for forecasting CME/ICME arrival time at Earth—the uniform acceleration/uniform velocity model. The model assumes: (1) For all CME/ICME events, ICME first undergoes an effective uniformly accelerated linear motion due to background solar wind effects, with acceleration $a$ linearly dependent on CME initial speed $u$:

$$a = \alpha - \beta u \quad (1)$$

$$s = ut + \frac{1}{2}at^2 \quad (2)$$

where $\alpha = 2.193$, $\beta = 0.0054$, and $t$ is the time for CME to propagate to distance $s$; (2) ICME maintains this variable-speed motion until a cutoff distance $d$ (typically 0.76 AU), after which it propagates at constant velocity. Therefore, the time required for CME/ICME to reach 1 AU is the sum of uniform acceleration time and uniform velocity time:

$$T = \frac{-u + \sqrt{u^2 + 2ad}}{a} + \frac{1\mathrm{AU} - d}{\sqrt{u^2 + 2ad}}$$

Gopalswamy et al. [5] applied this statistical forecasting model to 47 CME/ICME events from December 1996 to July 2000, obtaining a forecasting standard deviation of 10.7 hours.

## 3 Influence of Background Solar Wind Convection Effects on CME Transit Time

### 3.1 Selection and Analysis of 52 CME/ICME Sample Events

From ICME event lists during 1996-2007, we selected 52 CME/ICME events, as shown in . The main selection criteria were: (1) clear Earth-directed CME/ICME events recorded through solar activity monitoring and observations; (2) time intervals between successive CME events exceeding 2 days, ensuring "clean" CME/ICME samples with minimal interference; (3) relatively complete solar and interplanetary observational data for 3-4 consecutive days; and (4) resulting geomagnetic storm index Dst $< -50$ nT.

List of 52 CME/ICME events

*Note:* $V_{cme}$ *is CME initial speed,* $V_{sw}$ *is background solar wind speed,* $T_{obs}$ *is observed CME transit time, and* $T_e$ *is predicted CME transit time.*

Using the initial speeds of these 52 events with the Gopalswamy et al. [4-5] uniform acceleration/uniform velocity model, we obtained predicted transit times $T_e$. We defined the prediction error $dT$ as the difference between observed transit time $T_{obs}$ and predicted time $T_e$ ($dT = T_{obs} - T_e$). [Figure 1: see original paper] shows the relationship between transit time and CME initial speed for the 52 CME/ICME events, where plus signs represent observed events and the curve shows predictions from the Gopalswamy et al. [4-5] model. [Figure 2: see original paper] presents the prediction error distribution for the 52 CME/ICME events. The uniform acceleration/velocity model yielded a standard deviation of 16.5 hours for these 52 events. The error distribution does not follow a Gaussian distribution, with only 42% of events having prediction errors less than 15 hours and over one-fifth exceeding one day.

We used the difference between CME initial speed $V_{cme}$ and background solar wind speed $V_{sw}$ to characterize the convection effect of ICME propagation in fast versus slow background solar wind as a parameter affecting CME arrival time. Analyzing the relationship between $V_{cme} - V_{sw}$ and prediction error $dT$ for the 52 events ([Figure 3: see original paper]) yields the best-fit relationship:

$$dT = -15.9 + 0.0267 \times (V_{cme} - V_{sw}) \quad (4)$$

Using equation (4) to correct the Gopalswamy et al. [4-5] uniform acceleration/velocity model (equation (3)), the corrected CME transit time prediction formula becomes:

$$T_{corrected} = \frac{-V_{cme} + \sqrt{V_{cme}^2 + 2ad}}{a} + \frac{1\text{AU} - d}{\sqrt{V_{cme}^2 + 2ad}} + dT \quad (5)$$

Applying the corrected formula (5) to predict transit times for the 52 events yields the error distribution shown in [Figure 4: see original paper], with a corrected standard deviation of 11.4 hours. [Figure 4: see original paper] reveals: (1) the corrected prediction error distribution conforms to a Gaussian distribution; (2) after correction, 68% of events have prediction errors within 15 hours, with nearly all events (96%) within one day, and only two events exceeding one-day error.

These results demonstrate that considering convection effects of ICME propagation in fast and slow background solar wind effectively corrects CME transit time predictions. However, the corrected standard deviation remains above 10 hours, which is not ideal. Possible reasons include: (1) background solar wind convection is only one physical factor, with varying importance across different events; and (2) background solar wind motion in interplanetary space is time-varying and complex, while our assumption represents a significant simplification.

### 3.2 Ten CME/ICME Events Causing Major Geomagnetic Storms

Compared with typical CME/ICME events, those causing major geomagnetic storms (Dst $< -200$ nT) receive greater attention due to their more severe impacts and greater research significance. Therefore, from ICME event lists during 1996-2007, we selected 10 CME/ICME events causing major geomagnetic storms (Dst $< -200$ nT), as shown in .

List of 10 CME/ICME Events

*Note: $dT = T_{obs} - T_e$ represents the prediction error from the uniform acceleration/velocity model.*

Applying the Gopalswamy et al. [4-5] uniform acceleration/velocity model (equation (3)) to these 10 major CME events yielded predicted transit times $T_e$ and prediction errors $dT$ listed in , with a standard deviation of 10.6 hours. [Figure 5: see original paper] shows the relationship between transit time and CME initial speed for these events, while [Figure 6: see original paper] displays the prediction error distribution, which also does not follow a Gaussian distribution.

Considering the convection effect of ICME propagation in fast versus slow background solar wind as a factor influencing CME arrival time predictions, we analyzed the relationship between speed difference $V_{cme} - V_{sw}$ and prediction error $dT$ for the 10 events ([Figure 7: see original paper]), obtaining the best-fit relationship:

$$dT = -39.55 + 1.36 \times \sqrt{V_{cme} - V_{sw}} \quad (6)$$

Using equation (6) to correct the Gopalswamy et al. [4-5] model (equation (3)), the corrected prediction formula becomes:

$$T_{corrected} = \frac{-V_{cme} + \sqrt{V_{cme}^2 + 2ad}}{a} + \frac{1\text{AU} - d}{\sqrt{V_{cme}^2 + 2ad}} + dT \quad (7)$$

Reapplying the corrected formula (7) to predict transit times for the 10 events yields prediction errors of 13.58, −4.62, −12.04, 0.92, 1.31, −3.21, −12.77, 1.49, 14.77, and 0.39 hours, with a standard deviation of 6.5 hours. The error distribution is shown in [Figure 8: see original paper].

These results demonstrate that for CME/ICME events causing major geomagnetic storms (Dst $< -200$ nT), considering convection effects of ICME propagation in fast and slow background solar wind provides excellent correction to CME transit time predictions: (1) the standard deviation decreases from 10.6 hours to 6.5 hours, a reduction of 40%; (2) the error distribution changes from non-Gaussian to Gaussian; and (3) after correction, all events have prediction errors within 15 hours, with 60% of events having errors less than 5 hours.

## Conclusion

Using the Gopalswamy et al. uniform acceleration/velocity model as the forecasting "commonality," we statistically analyzed the physical "individuality" of convection effects in fast versus slow background solar wind on CME transit time predictions. Separate statistical analyses of 52 CME/ICME events related to geomagnetic effects (Dst $< -50$ nT) and 10 CME/ICME events causing major geomagnetic storms (Dst $< -200$ nT) during 1996-2007 demonstrate that considering convection effects of ICME propagation in different background solar wind conditions provides meaningful correction to CME transit time forecasts, confirming that solar wind convection effects constitute an important physical factor affecting statistical predictions of CME transit time.

However, due to insufficient observational data in interplanetary space between the Sun and Earth, combined with the complexity, dynamic nature, temporal variability, and coupling of the Sun-Earth system, accurate prediction of CME arrival time remains difficult. Convection effects in fast and slow background solar wind represent only one of several important physical factors influencing CME transit time. Other factors affecting CME transit time predictions include three-dimensional anisotropic flow of interplanetary solar wind, CME energy and release mechanisms ("impulsive" versus "piston-driven"), and interplanetary magnetic field configuration. Comprehensive investigation of their combined effects on interplanetary disturbance arrival times requires further research.

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