Estimation of the Transit Time of Multiple Coronal Mass Ejection Events

Firas Al-Hamdani(✉) and Doha Al-Feadh

Basrah University, Basra 61004, Iraq
firas.balbool@uobasrah.edu.iq

Abstract. We study the transit time (T.T) of triple events where the first two coronal mass ejections (CME) are associated with solar energetic particle events (SEP), while the third one is not. Our study focuses on the propagation of these CMEs and their associated shocks to estimate the best acceleration equation for T.T calculations and to determine the minimum error of the T.T of the CMEs. Using different models, we estimated the T.T of very high-speed CMEs and compared them with the empirical shock arrival model (ESA). Our results show that the acceleration cessation distance (ACD) in the ESA model yields the lowest possible T.T errors for the first event (0.7–0.5 AU) compared to other equations, and a distance of 0.7 AU for the second event. We also reveal minimum errors for the third event with a distance of 0.6 AU. In conclusion, these events exhibit different responses to the models used, even when they have very high speeds.

Keywords: Coronal mass ejections · Initiation and propagation · interplanetary shock wave

1 Introduction

Coronal mass ejections (CMEs) play a crucial role in space weather prediction, often resulting in the most intense geomagnetic disturbances on Earth (e.g., Gopalswamy et al. [1], Manoharan and Mujiber Rahman [2]; Shanmugaraju et al. [3]). These phenomena have been reported to affect Earth's atmosphere in various ways, with geomagnetic storms primarily caused by CMEs directed towards Earth. The direction, speed, magnitude, density, orientation, and magnetic field strength of CMEs near Earth are key determinants of their geo-effectiveness. Initially accelerated by the coronal magnetic field, CMEs may experience further acceleration mechanisms during their journey through space (Michalek et al. [5]).

Moreover, CMEs and solar flares are considered the most significant manifestations of solar activity, with their kinematics depending on initial velocity and solar wind conditions. The interaction between CMEs and their internal energy, as well as their interaction with each other, leads to constantly changing propagation dynamics between the Sun and Earth (e.g., Manoharan [6]).

Furthermore, coronal and/or CME-driven shocks produce solar radio type II bursts by accelerating electrons and transforming plasma oscillations into radio waves. Solar

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burst data confirming type II emission in the solar wind at radial locations as far out as 20 Rs-30 Rs are well-documented (Al-Hamadani et al. [7]). Numerous studies and models have been developed to anticipate acceleration processes, with some focusing on forecasting the arrival of interplanetary (IP) shocks caused by rapid CMEs (Smart and Shea [8]; Smith [9]). However, these models have demonstrated varying degrees of precision (e.g., Gopalswamy et al. [10]).

Gopalswamy et al. [11] introduced an empirical model based on observations from 1996 to 2000 to predict CME arrival time at 1 AU. They established an efficient acceleration equation (a = 2.193 − (0.0054 × u)), coinciding with the CME starting speed (u), and calculated travel time with minimal errors using an ESA model. Michalek et al. [5] examined the transit time (T.T) of 83 CMEs near Earth, deriving an effective acceleration equation (a = 4.11 − (0.0063 × u)). Additionally, they obtained another relationship for effective acceleration (a = 3.35 − (0.007 × u)) for very slow and very fast events, assuming no acceleration cessation distance (ACD) between the Sun and Earth.

In this study, we focus on triple events in sequence where solar energetic particle (SEP) increases are associated with the first two CMEs, while the third shows no signs of a SEP enhancement. Our objective is to investigate the acceleration processes of multiple solar eruptions during their transition in IP space. The selection criteria for the analyzed events are detailed further in Pohjolainen et al. [14].

2 Data Analysis

We analyzed a set of CMEs observed by *Solar and Heliospheric Observatory/Large Angle and Spectrometric Coronagraph* (SOHO/LASCO). These events show three distinct features: a quick halo-type CME, a propagating shock evident in radio emission, and powerful flares occur in the same active region (AR) one after the other. All CMEs associated with M and X class X-ray flares, the details of CMEs, shock wave arrival time and T.T are listed in the Table 1. Where the first three columns refer to the CME date, time and linear speed respectively. Next four columns show date, time, speed and the actual T.T of IP shock. The T.T of the CMEs and their shocks found from the time various between the first apparent of CMEs in the SOHO/LASCO and IP shock/ *interplanetary coronal mass ejections* (ICME) arrival time in *Advanced Composition Explorer* (ACE) and WINDs spacecraft. The shock wave details can be obtained by ACE/WIND spacecraft, one can calculate the speed of the shock wave as in the Table 1.

The ideal and vastly used empirical production model is the *empirical CME arrival* (ECA) and ESA models which is developed by Gopalswamy and his collaborated. We find the T.T by using Gopalswamy et al. (2001) and Kim, Moon and Cho (2007) model as stated below:

$$\boldsymbol{T}_1 = \frac{-\boldsymbol{u} + \sqrt{\boldsymbol{u}^2 + 2\boldsymbol{a}\boldsymbol{d}_1}}{\boldsymbol{a}} \tag{1}$$

$$\boldsymbol{T}_2 = \frac{\boldsymbol{d}_2}{-\boldsymbol{u} + \sqrt{\boldsymbol{u}^2 + 2\boldsymbol{a}}\boldsymbol{d}_1} \tag{2}$$

Table 1. CMEs and shock wave characteristics

CME			IP Shock/ACE				IP Shock/WIND			
Date	Time UT	Speed Km/s	Date	Arrival Time hh:mm	Shock speed Km/s	T.T hours	Date	Arrival Time hh:mm	Shock speed Km/s	T.T hours
24.11.00	05:30	1289	26.11.00	05:00	462	47.5	26.11.00	05:32	520	48.03
24.11.00	15:30	1245	26.11.00	11:24	632	43.9	26.11.00	11:43	666	44.21
09.04.01	15:54	1192	11.04.01	13:14	613	45.16	11.04.01	14:09	673	46.25
10.04.01	05:30	2411	11.04.01	15:28	731	33.96	11.04.01	16:18 18:18	828 830	34.8
11.04.01	13:31	1103	13.04.01	07:06	914	41.58				
22.08.05	01:31	1194	24.08.05	05:45	518	52.23	24.08.05	05:35	591	51.56
22.08.05	17:30	2378	24.08.05	08:20	795	38.83	24.08.05	08:24	525	38.9
23.08.05	14:54	1929	25.08.05	13:00		46.1				

The T.T formulated as ($T.T = T_1 + T_2$), where T_1 is a travel time till to ACD or acceleration distance d_1. Because the assumption is that the CME subjected to a constant acceleration or deceleration process during travel to the Earth with constant speed, T_2 is the travel time after the distance d_1 up to 1 AU. From the initial linear speed of CME we can found the effective IP acceleration by using different acceleration equations as below:

$$\boldsymbol{a} = 2.193 - (0.0054 \times \boldsymbol{u}) \quad (3)$$

$$\boldsymbol{a} = 4.11 - (0.0063 \times \boldsymbol{u}) \quad (4)$$

$$\boldsymbol{a} = 3.35 - (0.007 \times \boldsymbol{u}) \quad (5)$$

3 Models

Table 2 discusses the variations between the real arrival time of IP shock and T.T which is found from above equations with various acceleration distances. Where T.T error value is less than (6h of all equations) for the second CME at the first event, and less than (7h of all equations) for the first CME at the second event.

At the cessation acceleration distance (0.5 AU) the error in the T.T is minimum at Eq. 5 for all events compared with the other equations, as shown in Fig. 1.

The T.T profile was found from ESA model for all events with ACD (0.7) AU, drown to compared with the other acceleration equations and distances. Where we used the same way with the other acceleration equations(Eq. 4 and Eq. 5) to find the T.T. Table 2 explain that at 0.7 AU the ACD produced minimum errors of T.T for Eq. 3

Table 2. T.T difference for various ACD. The bold values exhibit the smallest variation (<7 h) between the actual and estimated T.T, ΔT equal to the difference between actual T.T of IP shocks and estimate T.T.

Date	ΔT (hours) for Eq. (3)			ΔT(hours) for Eq. (4)			ΔT(hours) for Eq. (5)		
CME	0.7 A.U	0.6 A.U	0.5 A.U	0.7 A.U	0.6 A.U	0.5 A.U	0.7 A.U	0.6 A.U	0.5 A.U
24.11.00	**4.89**	**6.55**	8.19	7.63	8.69	9.82	**0.26**	**3.27**	**5.85**
24.11.00	**−0.84**	**0.97**	**2.75**	**2.41**	**3.50**	**4.67**	**−5.77**	**−2.47**	**0.31**
09.04.01	**−1.31**	**0.71**	**2.67**	**2.68**	**3.81**	**5**	**−6.61**	**−2.93**	**0.11**
10.04.01	14.56	14.89	15.27	14.47	14.81	15.20	13.44	13.96	14.52
11.04.01	−10.78	−8.33	**−6.02**	**−5.14**	**-3.99**	**−2.76**	−16.65	−12.27	−8.73
22.08.05	**4.09**	**6.12**	8.06	8.06	9.18	10.38	**−1.81**	**2.47**	**5.51**
22.08.05	18.33	18.68	19.07	18.25	18.60	19.01	17.17	17.72	18.30
23.08.05	19.78	20.37	21	19.94	20.49	21.1	17.89	18.85	19.83

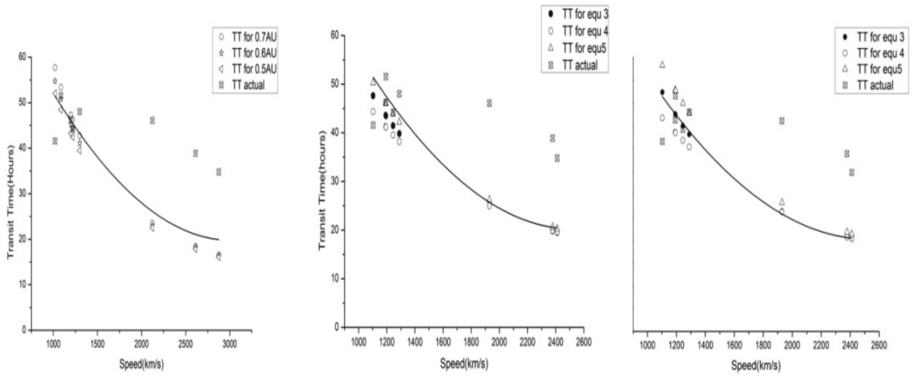

Fig. 1. The T.T of various acceleration distances. The left panel at 0.7AU, the middle panel at 0.6 AU and the right panel at 0.5 AU with different acceleration equations. The solid line indicates to the T.T from ESA model with cessation acceleration distance 0.7 AU.

to the events (1 and 2) comparing with the other equations, same thing applied to 0.6 AU acceleration distance. For the third event all ACD gives minimum error at Eq. 5, because this equation used either for very slow speed or very high speed events. The above procedure for estimate T.T was repeated but with the linear speed of CMEs at distances 20 Rs as explain in Table 3 to make a comparison of T.T with different speed.

Then we make graphically compression between the T.T obtained from the second order speed of CMEs reported in the SOHO/LASCO catalogue and final speed and used them in Eq. 3 with $d_1 = 0.7$ AU. From the Table 3, the first event T.T error is less than (9 h) at first CME, and less (5 h) for second CME. Second event errors less than (6 h)for first CME, and about (10–19 h) for the other CMEs, same result for the third CME but with the error limits in the T.T about (21 h) in the last two CMEs. Approximately the same result we can get for the final speed (right panel in Fig. 2) because there is no big differences between the second order speed at final distance and second order speed at 20 Rs distance in this events.

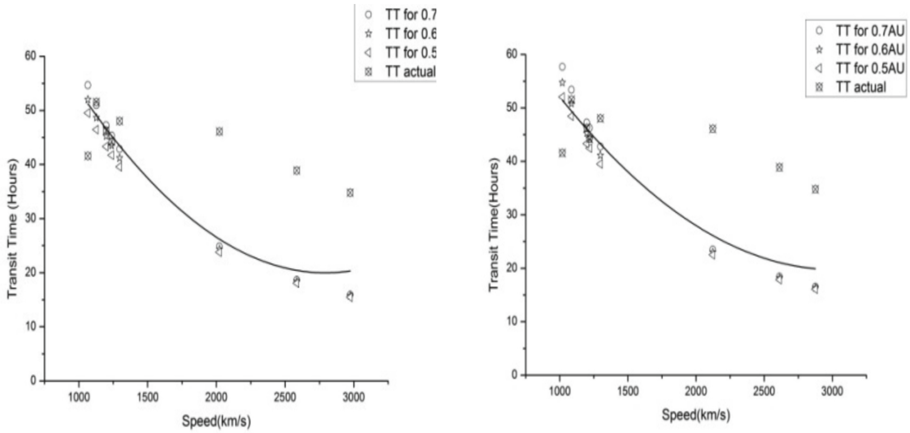

Fig. 2. Theestimated T.T using second order speed 20 Rs (left panel), and second order speed at final distance (right panel). Solid line refers to the ESA model for ACD 0.7.

4 Comparison with Other Models

We made a comparison between the actual T.T with different models such as; (1) Schwenn et al. [15], expansion speed model (2) Kim, Moon and Cho [16] model, and (3) Vrsnak et al. [12], *drag based model* (DBM). The expansion model based from the relation:

$$T_{arr} = 203 - 20.77 \times ln(V_{CME}),$$

where T_{arr} (in hours) is the T.T of linear speed V_{CME} in (km/s) of CME. Kim, Moon and Cho [16] indicate that the constant IP acceleration in the ESA model does not apply for all CME events, so that thy derived linear fit to the relationship between shock T.T (in hours) and V_{CME} in (km/s) during solar maximum, $T_{arr} = 76.86 - 0.02 \times (V_{CME})$. The DBM based on the motion of equation on CME where the drag acceleration /deceleration have quadratic dependence on therelative speed between CMEs and the background solar wind.

Table 4 and Fig. 3, reveals the variation between different models and actual T.T, for DBM we calculate the T.T based on basic solar wind speed parameters 450 km/s and the drag parameter (γ) as 0.2×10^{-7} km/s. The drag model gives in general the better result for minimum errors of T.T comparing with other models and its close to the real observed T.T, this result can be seen obviously in the Fig. 3. Where left side of Fig. 3

Table 3. The T.T differences for various ACD at 20 Rs. The bold values show the minimum difference (<7 h) between the actual and estimated T.T. ΔT equal to the difference between the actual T.T of IP shocks and the estimate T.T.

Date	ΔT (hours) for Eq. (3)			ΔT(hours) for Eq. (4)			ΔT(hours) for Eq. (5)		
CME	0.7 A.U	0.6 A.U	0.5 A.U	0.7 A.U	0.6 A.U	0.5 A.U	0.7 A.U	0.6 A.U	0.5 A.U
24.11.00	**5.18**	**6.55**	8.19	7.63	8.69	9.82	**0.26**	**3.27**	**5.85**
24.11.00	**−0.84**	**0.97**	**2.75**	**2.41**	**3.5**	**4.67**	**−5.77**	**−2.47**	**0.31**
09.04.01	**−1.31**	**0.719**	**2.67**	**2.89**	**4.01**	**5.20**	**−6.27**	**−2.64**	**0.38**
10.04.01	14.56	14.89	19.31	18.74	18.96	19.21	18.19	18.49	18.83
11.04.01	−13.08	−10.42	−7.94	**−6.55**	−5.41	−4.18	−19.14	−14.44	10.69
22.08.05	**0.56**	**2.90**	**5.10**	**5.71**	**6.85**	8.08	**−5.16**	**−0.97**	**2.42**
22.08.05	20.22	20.50	20.82	20.10	20.40	20.74	19.72	19.70	**2.18**
23.08.05	21.22	21.74	22.30	21.29	21.79	22.35	19.52	20.37	21.24

Table 4. Variations between the projected T.T for different models and the real IP shock T.T. The bold values show the minimum difference (<7 h) between the actual and estimated T.T.

Date	Expansion model	Kim model	Drag based model
24.11.00	**−6.22**	**−3.05**	**4.25**
24.11.00	−10.76	**−7.5**	**−0.37**
09.04.01	−9.62	**−6.77**	**0.65**
10.04.01	**−6.44**	**6.16**	**3.37**
11.04.01	−15.90	−13.22	**−5.9**
22.08.05	**−4.28**	**−1.42**	**6**
22.08.05	**−2.63**	9.6	**7.23**
23.08.05	**0.22**	7.82	10.66

show different T.T models with the linear speed of CMEs while right side with linear speed at distance 20 Rs.

When the CMEs emanating from the disk center or closed to it, there are projection effects at these disc-centered events. (Gopalswamy et al. [11]; Gopalswamy et al. [17]; Michalek et al. [5]; Shanmugaraju et al. [17]; Nicewicz and Michalek (2014)). To get rid from the projection effects we will use Gopalswamy et al. [11] Eqs. (6, 7) and Nicewicz and Michalek [18] Eq. 8.

$$v = u * \left\lfloor \frac{\sin\varphi + 1}{\sin\alpha + \sin\varphi} \right\rfloor \tag{6}$$

$$\varphi = arc\cos(\cos\lambda\cos\theta) \tag{7}$$

Table 5. The T.T following projected adjustment in the CME speed with the use of formulas (6, 7). The bold values show the minimum difference (>7 h) between the actual and estimated T.T.

Date	ΔT (hours) for Eq. (3)			ΔT(hours) for Eq. (4)			ΔT(hours) for Eq. (5)		
CME	0.7 A.U	0.6 A.U	0.5 A.U	0.7 A.U	0.6 A.U	0.5 A.U	0.7 A.U	0.6 A.U	0.5 A.U
24.11.00	20.40	21.05	21.74	20.64	21.25	21.90	18.31	19.40	20.48
24.11.00	14.96	15.69	16.47	15.34	16	16.71	12.63	13.87	15.06
09.04.01	15.78	16.58	17.42	16.28	16.98	17.74	13.26	14.62	16.94
10.04.01	21.10	21.25	21.42	20.97	21.13	21.32	20.59	20.81	21.05
11.04.01	**5.78**	6.91	8.07	**6.9**	7.87	8.81	**2.39**	**4.38**	**6.20**

Table 6. T.T following the adjustment of the projection in the CME speed by using Eq. (8). The bold values show the minimum difference (<7 h) between the actual and estimated T.T.

Date	ΔT (hours) for Eq. (3)			ΔT(hours) for Eq. (4)			ΔT(hours) for Eq. (5)		
CME	0.7 A.U	0.6 A.U	0.5 A.U	0.7 A.U	0.6 A.U	0.5 A.U	0.7 A.U	0.6 A.U	0.5 A.U
24.11.00	11.27	12.46	13.68	12.64	13.55	14.52	7.72	9.83	11.75
24.11.00	28.24	28.44	28.67	28.10	28.32	28.57	27.54	27.85	28.18
09.04.01	9.49	10.68	11.90	10.86	11.77	12.74	**5.94**	8.05	9.97
10.04.01	18.83	19.26	19.26	18.69	18.91	19.16	18.13	18.44	18.77
11.04.01	**1.10**	**2.56**	**4.02**	**3.21**	**4.22**	**5.28**	**−3.08**	**−0.45**	**1.84**

$$V = \upsilon LASCO + \upsilon LASCO * 0.23 \tag{8}$$

where V is the corrected speed and u is the linear speed of the CME, α is the cone angle 360, λ and φ are the latitude and the longitude can be obtain from are location, v LASCO is the linear speed of CME. The T.T errors after using correction speed are given in Table 5 for Gopalswamy et al. [11] correction speed and Table 6 for Nicewicz and Michalek [18] speed. Form the Table 4 the T.T reduced for all equation for the last CME of second event and same thing is occur by using Nicewicz and Michalek [18] speed. Nevertheless, as indicated by Zhao and Dryer [19], Several factors, including the following, might contribute to the uncertainty in the T.T calculation: (1) the IP coronal mass ejections (ICMEs) 3D morphology, (2) the impact of the solar wind background, (3) variation in the ICMEs propagation, (4) the fluctuations in the solar wind and in homogeneities (5) T.T interactions with other structures, etc.

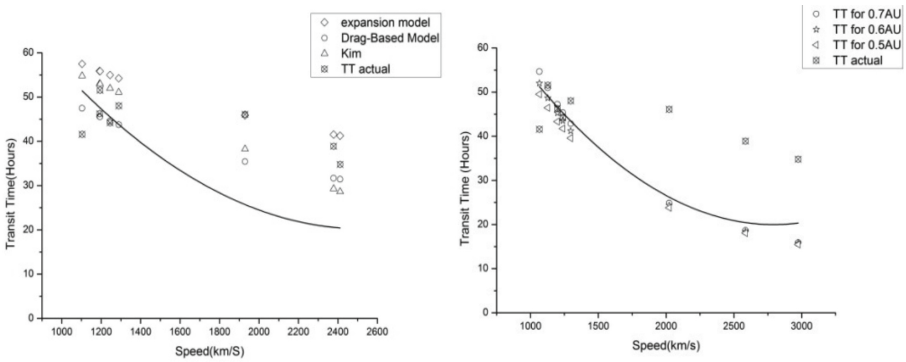

Fig. 3. Comparison between observed T.T and various T.T in different models. Solid line indicate ESA model for 0.7 AU ACD. Where the left side show different T.T models with the linear speed of CMEs while right side with linear speed at distance 20 Rs.

5 Conclusions

In this study, we focused on the transit time (T.T) of triple events involving coronal mass ejections (CMEs), where two CMEs were associated with solar energetic particle (SEP) enhancements, while the third CME did not exhibit enhancement in SEP observation. Radio emission observations confirmed that all these events had shocks propagating in the interplanetary (IP) medium (Pohjolainen, Al-Hamadani, and Valtonen [14]).

To investigate the propagation of these events in the IP medium, we calculated the T.T for each event. Linear CME speeds were used in various acceleration equations to evaluate the IP accelerations. These IP acceleration values were then applied in the ESA model with different acceleration distances. We also applied the same process using linear speed at 20 Rs distance to study the effects of speed differences on the estimated T.T. However, no distinct changes were observed in the T.T.

Our analysis revealed that the T.T errors were minimum for acceleration Eq. (5) in the ESA model with an acceleration cessation distance (ACD) of (0.7–0.5) AU for event (1) compared to other equations. Similarly, Eq. 3 with a distance of (0.7) AU yielded minimum errors for event (2), while Eq. 5 showed minimum errors for event (3) with a distance of (0.6) AU.

Furthermore, we estimated the T.T after correcting for the projection effect (correction speed), and found that the minimum errors occurred in Eq. 5 after using the Nicewicz and Michalek [18] equation.

Based on these conclusions, we can estimate the T.T for the third CME of event (1) using Eq. 5 with an acceleration distance of (0.5) AU to be (64.84 h), with the shock arrival time on 26th November 2000 at (16:50 min). The Double Bayesian Model (DBM) expected the CME arrival at the target (date and time) on 26th November 2000 at (23 h:57 min) with a T.T of 49.86 h, and the impact speed at the target (at 1 AU) to be 635 km/s

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