Earth Moon Planets (2012) 109:13–27
DOI 10.1007/s11038-012-9398-7

# On the Interplanetary Coronal Mass Ejection Shocks in the Vicinity of the Earth

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Received: 25 August 2011 / Accepted: 30 July 2012 / Published online: 13 November 2012


**Abstract** We studied the relation between the near-Earth signatures of the interplanetary coronal mass ejections (ICMEs) shocks such as sudden storms commencement (SSC), and their counterparts of coronal mass ejections (CMEs) observed near-Sun by solar and heliospheric observatory (SOHO)/large angle and spectrometric coronagraph (LASCO) coronagraph during 1996–2008. Our result showed that there is a good correlation between the travel time of the ICMEs shocks and their associated radial speeds. Also we have separated the ICME shocks into two groups according to their effective acceleration and deceleration. The results showed that the faster ICME shocks (with negative accelerations which decelerated by solar wind plasma) are more correlated to their associated travel time than those with positive accelerations.

**Keywords** Coronal mass ejection · Interplanetary coronal mass ejection · Sudden storms commencement

## 1 Introduction

The coronal mass ejections (CMEs) are thought to be the main geoeffective objects that produce geomagnetic storms, which can affect the Earth. Therefore, the estimation of the arrival time of CMEs in the Earth vicinity is very important in space weather investigations. 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 (Gopalswamy et al. 2001b). Fast CMEs are decelerated mostly by the solar wind due to friction which is proportional to the square of the velocity difference (Michałek et al. 2004). For building the science-based prediction scheme of space weather, it is important to track the solar disturbances generated shocks and their interactions. Using numerical simulation, Wang and Burlaga (1986) investigated the interactions of interplanetary shock waves beyond 1 AU. An example is the case when a fast forward shock overtakes and interacts with a fast reverse shock from a preceding event (Smith et al. 1986). CMEs are found to be the primary source of transit interplanetary (IP) disturbances which cause

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geomagnetic storms (Gopalswamy et al. 2000). Combining CME observations made by solar and heliospheric observatory (SOHO)/large angle and spectrometric coronagraph (LASCO) and ICMEs measurements near the earth (Gopalswamy et al. 2000, 2001 and 2004) developed an empirical model to predict 1 AU arrival time of the CMEs. The model was based on the fact that the range of velocity distribution of ICMEs, detected by the Wind spacecraft was much narrower (in the range 350–650 km $s^{-1}$) in comparison to the velocity distribution of CMEs observed by SOHO/LASCO near the sun (in the range 150–1,050 km $s^{-1}$). Gopalswamy et al. (2000) correlated near-Earth observations of ICMEs detected by the Wind spacecraft with their near-Sun counterparts observed by the solar and SOHO coronagraphs, they used the initial CME velocities to estimate the CME acceleration. This method cannot help us to select all CME events which directed toward to the Earth. This method is good with energetic events only. Cane and Richardson (2003) used the ICMEs too, but they created the CMEs–ICMEs list by manual selection using the solar wind signatures. Schwenn et al. (2005) have studied the association CME with their effects near the Earth by using 181 CMEs obtained from LASCO from January 1997 to 15th April 2001; they found that, there is a unique association between CMEs on the sun and subsequent 50.3 % ICMEs observed near the Earth in out of all 180 cases.

In this paper, we studied the relation between the near-Earth signatures of the ICMEs shocks and their counterparts of CMEs observed near-Sun by SOHO/LASCO coronagraph during 1996–2008. Also we have separated the ICME shocks into two groups according to their effective acceleration and deceleration.

## 2 Data Sources

We used 13,863 records of CMEs data obtained from CME Catalogue which observed by SOHO/LASCO, during the solar cycle 23rd (1996–2008). These CME data are available in the CDA website:http://cdaw.gsfc.nasa.gov/CME_list/catalog_description.htm Gopalswamy et al. (2000).

This catalog contains all CMEs used the same ICMEs to create a list of correlate CME–ICME events by manually identified since 1996 from the LASCO SOHO mission. LASCO has three telescopes C1, C2, and C3. However, only C2 and C3 data are used for uniformity because C1 was diabled in June 1998. At the outset, we would like to point out that the list is necessarily incomplete because of the nature of identification. In the absence of a perfect automatic CME detector program, the manual identification is still the best way to identify CMEs. This data base will serve as a reference to validate automatic identification programs being developed. We also used the X-ray data which was measured and provided by Geostationary Operational Environmental Satellite (GEOS), during the same interval (1996–2006) with 22,688 records flare events. In addition we obtained the Data of the sudden storms commencement (SSC) events from preliminary reports of the ISGI (Institute de Physique du Globe, France); during this period we selected 345 SSC, events and 13,863 CME events.

## 3 Methodology

### 3.1 Model Outline

Gopalswamy et al. (2000a, 2001a) developed an empirical model to predict the 1 AU arrival times of CMEs. The model was based on the velocity distribution of ICMEs detected by Wind and ACE spacecrafts (near-Earth) in comparison to the velocity

distribution of CMEs observed by SOHO/LASCO (near-Sun). By comparing between two distribution speeds of CMEs, Gopalswamy suggested that CMEs undergo an effective acceleration defined as a = (u − v)/t where u is the initial velocity near-Sun detected by (SOHO/LASCO), is the final velocity detected by Wind and t is the time taken by a given CME to reach Earth. By these assumption we can obtain an expected relation between effective acceleration a, and initial velocity u according to the kinematics equation

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

The only free parameter required by the model is the initial CME velocity to predict the arrival time t at distance S = 1 AU. To generalize the model, Gopalswamy et al. (2001a) assumed that effective acceleration ceases at some distance d between Sun and Earth. The CMEs travel with constant speed beyond $d_1$ to reach a point near-Earth at distance $d_2$, the travel time then is the sum of time $t_1$ taken to travel the distance $d_1$ and $t_2$ that to travel $d_2$, i.e., $t = t_1 + t_2$. The model predicted the travel time within mean error of 10.7 h considering the best cessation distance is at 0.75 AU).

We used this model by solving Eq. (1) for $t = T_C$, S = D and $u = V_{CME}$, where, $T_C$ is the calculated arrival time of ICME shocks, $V_{CME}$ is the initial velocity of the ICME, and D is the distance from the sun to the Earth's magnetosphere, since the height of the Earth's magnetosphere for the surface of the Earth = 10 $R_E$ ($R_E$ is the Earth's radius). Therefore D can be calculated from the equation:

$$\mathrm{D} = 1\mathrm{AU} - 10\mathrm{RE} \tag{2}$$

$V_{CME}$ is corrected according to the projection effect of ICMEs with the assumption that each CME is like a cone with the front described by an arc of a circle, Hundhausen et al. (1994, see also Leblanc et al. (2001)) derived a formula to relate the real radial speed of the CME, $V_{rad}$, to its apparent velocity measured on the plane of the sky, $V_{sky}$, which reads as:

$$V_{rad} = V_{Sky}\frac{1 + \sin\alpha}{\sin\phi + \sin\alpha} \tag{3}$$

where, α is 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 cosφ = cosλ cosψ, where λ and ψ are the corresponding latitude and longitude of the source region center, respectively.

We can correct the calculated arrival time from:

$$T_{Error} = \mathrm{Min}\{|T_c - T_{SSC}|\}, \tag{4}$$

where, $T_{SSC}$ is the actual arrival time of the ICME shock impacted the magnetosphere and cause the a SSC, $T_{Error}$ is the error of the calculated arrival time, and:

$$T_{\min} < T_{SSC} < T_{\max}, \tag{5}$$

where $T_{\min}$ and $T_{\max}$ are minimum and maximum times as a boundary conditions for our model.

In the second step, we estimate the boundary intervals from Fig. 1 as follows: $T_{\min} \approx 1$ day and $T_{\max} \approx 7$ days.

### 3.2 Estimation of the Boundary Conditions

The CME–SSC interval must be between $T_{\min}$ and $T_{\max}$, to estimate these values we will need to create a program based on the following steps:

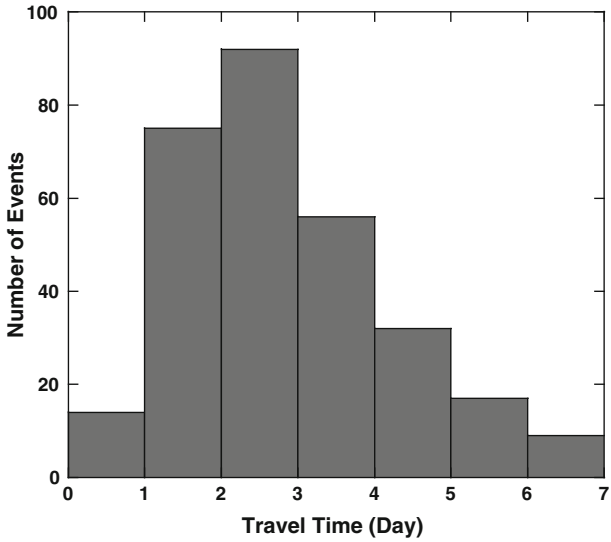


**Fig. 1** Histogram of the travel time of the ICME shock

- Reading the data of both CME and SSC (the signature of the arrival of ICME shock).
- Correct $V_{CME}$ according to the projection effect of ICMEs by applying Eq. (3)
- Estimate the arrival time TC by using Eq. (1).
- Calculate the intervals between SSC event and the corresponding ICME shocks by using Eq. (3)
- Selecting the CME–ICME shock event which has the minimum value of $T_{Error}$.

### 3.3 Selection of the CME–ICME Shocks Associated Events

Now, we have two data sets one for ICMEs near the sun and the other for SSC events in the vicinity of the Earth's magnetosphere, also we have selected the boundary intervals, and then we created a FORTRAN program with the following steps for selecting the ICME shock events:

Read the data of both ICMEs and SSC events.
Estimate arrival time Tc by using Eq. (1).
Apply the condition (4).
Find the nearby ICME event to the associated SSC by using Eq. (3).
Select the result values of ICME–SSC associated events.

## 4 Results and Discussions

### 4.1 Travel Time of the ICME Shock

By applying the steps of the FORTRAN program found in Sect. 3.3, we succeeded to select 295 ICME shock associated events and Fig. 1 showed the histogram of the travel time of these selected.

Our main result is expressed in Fig. 2, from which, we found that the best empirical equation between the travel time, $T_C$ of the ICME shocks and their associated corrected CME Velocities $V_{CME}$ is given by:

$$T_C = (854.52)(V_{ICME})^{(-0.57106)} \pm (0.22) \quad (6)$$

This equation have correlation coefficient, R = 0.60 for our 295 CME–ICME shock associated events. From which we found that there is a good correlation between the CMEs and their ICME shocks reached the Earth's magnetosphere and caused a SSC event as shown in Fig. 2. Moreover from this figure, we found that the Fast CMEs shock the Earth's Magnetosphere in short period while slow CMEs impact the Earth in long period.

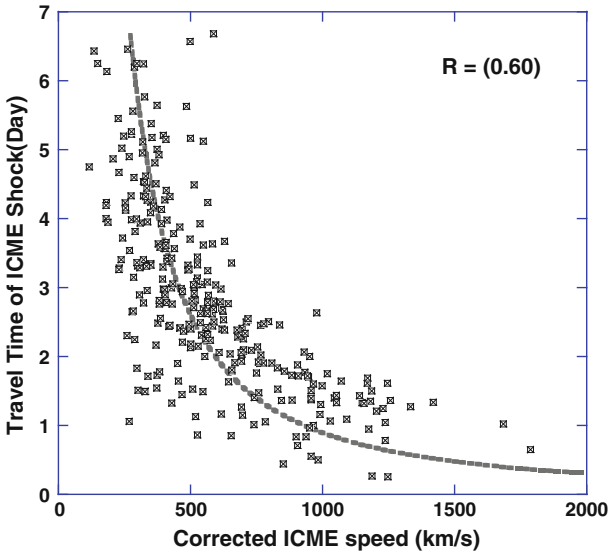


**Fig. 2** The travel time of ICME shocks

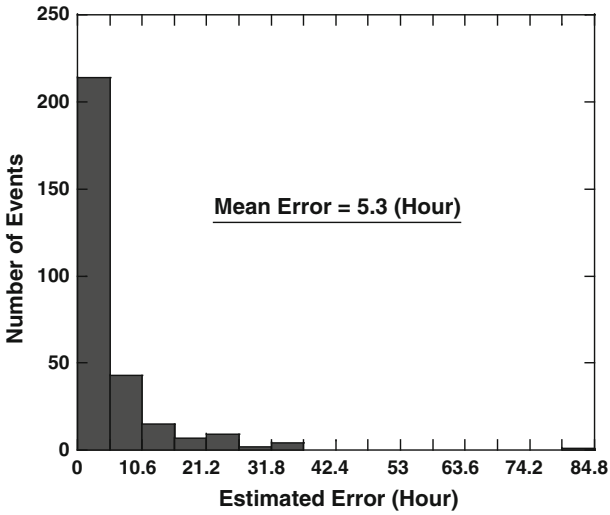


**Fig. 3** The estimated error of the prediction curve of Fig. 2

**Table 1** CME–ICME shocks associated list

| Interval[a] | SSC time | CME time | PA | Width | LS | IS | FS | S20 | Accl | E |
|---|---|---|---|---|---|---|---|---|---|---|
| 6.46 | 4/8/1996 13:34 | 4/2/1996 2:36 | 267 | 37 | 192 | 116 | 263 | 246 | 2.7 | 1.40E + 29 |
| 8.15 | 7/28/1996 13:07 | 7/20/1996 9:28 | 31 | 175 | 246 | 56 | 429 | 477 | 9.4 | 3.90E + 29 |
| 6.72 | 11/11/1996 15:27 | 11/4/1996 22:15 | 260 | 20 | 573 | 408 | 726 | 1044 | 41.7 | 1.50E + 29 |
| 7.39 | 12/2/1996 10:01 | 11/25/1996 0:40 | 261 | 63 | 258 | 266 | 250 | 239 | 90.6 | 2.30E + 28 |
| 1.75 | 12/14/1996 8:25 | 12/12/1996 14:30 | 94 | 46 | 206 | 139 | 266 | 362 | 5.5 | 1.00E + 28 |
| 2.3 | 1/10/1997 1:04 | 1/7/1997 17:45 | 84 | 52 | 156 | 43 | 260 | 423 | 9.2 | 1.70E + 29 |
| 0.63 | 1/11/1997 1:16 | 1/10/1997 10:04 | 85 | 57 | 325 | 350 | 297 | 297 | 91.5 | 4.50E + 29 |
| 8.69 | 2/9/1997 18:10 | 2/1/1997 1:37 | 95 | 59 | 218 | 182 | 254 | 351 | 4.1 | 1.10E + 29 |
| 2.79 | 5/25/1997 14:34 | 5/22/1997 19:30 | 102 | 66 | 346 | 298 | 394 | 507 | 7.5 | 3.90E + 29 |
| 7.45 | 5/26/1997 9:57 | 5/18/1997 23:13 | 88 | 32 | 353 | 92 | 624 | 650 | 17.6 | 1.00E + 30 |
| 7.49 | 6/19/1997 0:32 | 6/11/1997 12:48 | 93 | 53 | 94 | 98 | 90 | 34 | 90.4 | 1.70E + 28 |
| 4.95 | 6/22/1997 3:13 | 6/17/1997 4:30 | 69 | 79 | 185 | 157 | 213 | 312 | 3.2 | 4.00E + 28 |
| 0.76 | 7/15/1997 3:11 | 7/14/1997 8:51 | 77 | 82 | 258 | 275 | 238 | 237 | 90.8 | 1.00E + 30 |
| 2.33 | 8/3/1997 10:42 | 8/1/1997 2:40 | 97 | 53 | 183 | 172 | 192 | 318 | 3.1 | 6.80E + 27 |
| 3.89 | 9/2/1997 22:59 | 8/30/1997 1:30 | Halo | 360 | 371 | 291 | 460 | 551 | 9.3 | 1.20E + 30 |
| 1.27 | 9/21/1997 16:51 | 9/20/1997 10:20 | 272 | 97 | 777 | 725 | 827 | 803 | 5 | 1.50E + 31 |
| 1.27 | 10/1/1997 0:59 | 9/29/1997 18:30 | 78 | 99 | 369 | 344 | 391 | 421 | 2.5 | 2.30E + 30 |
| 0.45 | 10/10/1997 16:12 | 10/10/1997 5:20 | 100 | 84 | 308 | 340 | 275 | 239 | 92.5 | 3.10E + 29 |
| 9.84 | 10/23/1997 8:04 | 10/13/1997 11:51 | 265 | 94 | 323 | 283 | 364 | 356 | 2 | 1.50E + 30 |
| 5.27 | 10/24/1997 11:14 | 10/19/1997 4:42 | 92 | 63 | 373 | 381 | 364 | 358 | 90.7 | 6.50E + 29 |
| 6.55 | 11/6/1997 22:48 | 10/31/1997 9:30 | 262 | 65 | 631 | 309 | 984 | 845 | 26.2 | 5.70E + 30 |
| 4.06 | 11/22/1997 9:49 | 11/18/1997 8:27 | 272 | 75 | 444 | 362 | 529 | 505 | 5.2 | 3.70E + 30 |
| 5.71 | 11/30/1997 8:09 | 11/24/1997 15:06 | 69 | 19 | 559 | 710 | 404 | 444 | 913 | 2.10E + 29 |
| 8.25 | 12/30/1997 2:09 | 12/21/1997 20:10 | 281 | 77 | 126 | 91 | 162 | 215 | 1.7 | 1.60E + 28 |
| 7.3 | 1/6/1998 14:16 | 12/30/1997 7:08 | 85 | 56 | 443 | 481 | 406 | 251 | 97.1 | 2.60E + 29 |

**Table 1** continued

| Interval[a] | SSC time | CME time | PA | Width | LS | IS | FS | S20 | Accl | E |
|---|---|---|---|---|---|---|---|---|---|---|
| 9.14 | 1/24/1998 5:29 | 1/15/1998 2:10 | 92 | 51 | 297 | 288 | 305 | 333 | 1.2 | 5.00E + 28 |
| 2.65 | 3/4/1998 11:56 | 3/1/1998 20:13 | 268 | 71 | 242 | 156 | 319 | 744 | 22.8 | 1.80E + 29 |
| 0.19 | 4/16/1998 21:22 | 4/16/1998 16:55 | 297 | 49 | 470 | 445 | 495 | 495 | 2 | 8.10E + 29 |
| 0.48 | 4/23/1998 18:25 | 4/23/1998 6:55 | 308 | 20 | 646 | 724 | 565 | 593 | 97.6 | 1.70E + 30 |
| 6.42 | 5/8/1998 9:52 | 5/1/1998 23:40 | Halo | 360 | 585 | 511 | 657 | 627 | 8 | 1.20E + 31 |
| 0.17 | 5/29/1998 15:36 | 5/29/1998 11:27 | 73 | 63 | 224 | 235 | 212 | 108 | 91.8 | 6.70E + 28 |
| 4.76 | 6/5/1998 9:41 | 5/31/1998 15:27 | 137 | 28 | 637 | 537 | 737 | 824 | 16.9 | 6.90E + 29 |
| 3.65 | 6/13/1998 19:25 | 6/10/1998 3:55 | 109 | 144 | 562 | 588 | 534 | 537 | 92.5 | 8.20E + 29 |
| 2 | 3/10/1999 1:30 | 3/8/1999 1:26 | 102 | 60 | 536 | 394 | 681 | 1080 | 43.4 | 8.00E + 29 |
| 0.39 | 3/29/1999 1:52 | 3/28/1999 16:30 | 355 | 35 | 304 | 290 | 319 | 351 | 1.7 | 1.00E + 29 |
| 2.9 | 4/16/1999 11:25 | 4/13/1999 13:54 | 109 | 89 | 258 | 196 | 324 | 336 | 3.6 | 2.10E + 30 |
| 2.4 | 5/5/1999 15:43 | 5/3/1999 6:06 | Halo | 360 | 1584 | 1511 | 1658 | 1628 | 15.8 | 1.30E + 32 |
| 3.1 | 5/18/1999 0:56 | 5/14/1999 22:26 | 141 | 43 | 223 | 235 | 210 | 18 | 92.4 | 1.30E + 29 |
| 2.81 | 6/26/1999 20:16 | 6/24/1999 0:54 | 256 | 98 | 503 | 488 | 517 | 531 | 1.8 | 2.00E + 30 |
| 5.02 | 7/2/1999 0:59 | 6/27/1999 0:30 | 271 | 76 | 232 | 223 | 241 | 320 | 2.2 | 2.50E + 29 |
| 3.9 | 7/6/1999 15:09 | 7/2/1999 17:30 | 39 | 127 | 410 | 321 | 500 | 453 | 4.2 | 6.90E + 30 |
| 4.81 | 7/12/1999 2:18 | 7/7/1999 6:54 | 244 | 33 | 371 | 377 | 365 | 332 | 91.4 | 6.40E + 28 |
| 1.16 | 8/4/1999 2:19 | 8/2/1999 22:26 | 271 | 157 | 292 | 284 | 299 | 317 | 0.9 | 5.80E + 29 |
| 2.8 | 8/8/1999 18:41 | 8/5/1999 23:26 | 258 | 73 | 217 | 212 | 223 | 234 | 0.4 | 7.50E + 29 |
| 6.3 | 8/15/1999 10:44 | 8/9/1999 3:26 | 197 | 212 | 395 | 425 | 361 | 288 | 94.1 | 8.10E + 29 |
| 0.25 | 9/12/1999 3:59 | 9/11/1999 21:54 | 35 | 120 | 1680 | 1766 | 1591 | 1653 | 920 | 3.70E + 31 |
| 9.62 | 9/15/1999 7:53 | 9/5/1999 16:54 | 6 | 68 | 278 | 289 | 266 | 178 | 92.2 | 1.00E + 29 |
| 2.74 | 9/15/1999 20:19 | 9/13/1999 2:30 | 343 | 33 | 652 | 703 | 601 | 520 | 910 | 7.00E + 29 |
| 0.31 | 9/22/1999 12:22 | 9/22/1999 4:54 | 78 | 72 | 516 | 481 | 551 | 734 | 13.9 | 5.20E + 29 |
| 3.01 | 10/21/1999 2:25 | 10/18/1999 2:06 | 298 | 26 | 1081 | 1141 | 1021 | 979 | 915 | 2.20E + 30 |

**Table 1** continued

| Interval[a] | SSC time | CME time | PA | Width | LS | IS | FS | S20 | Accl | E |
|---|---|---|---|---|---|---|---|---|---|---|
| 5.95 | 10/28/1999 12:16 | 10/22/1999 13:26 | 305 | 118 | 478 | 561 | 393 | 440 | 95.8 | 4.30E + 30 |
| 0.49 | 11/5/1999 20:10 | 11/5/1999 8:26 | 72 | 66 | 284 | 258 | 309 | 386 | 3.4 | 4.40E + 29 |
| 8.68 | 12/12/1999 15:51 | 12/3/1999 23:30 | 249 | 52 | 330 | 283 | 382 | 450 | 5.8 | 3.10E + 28 |
| 5.15 | 1/11/2000 14:26 | 1/6/2000 10:54 | 311 | 7 | 472 | 342 | 599 | 1351 | 70.7 | 5.00E + 28 |
| 3.83 | 1/27/2000 14:53 | 1/23/2000 18:54 | 235 | 70 | 388 | 501 | 272 | 229 | 98.7 | 6.90E + 29 |
| 5.01 | 2/5/2000 15:44 | 1/31/2000 15:30 | 117 | 67 | 398 | 421 | 374 | 321 | 93.2 | 6.00E + 29 |
| 6.17 | 2/11/2000 23:52 | 2/5/2000 19:54 | 60 | 76 | 632 | 764 | 500 | 602 | 99.7 | 9.10E + 30 |
| 1.78 | 2/14/2000 7:31 | 2/12/2000 12:54 | 342 | 62 | 122 | 77 | 170 | 366 | 5.3 | 1.40E + 29 |
| 0.35 | 3/29/2000 19:24 | 3/29/2000 10:54 | Halo | 360 | 949 | 946 | 953 | 951 | 0.4 | 3.00E + 31 |
| 0.51 | 4/6/2000 16:39 | 4/6/2000 4:30 | 281 | 84 | 524 | 515 | 534 | 558 | 2 | 8.50E + 29 |
| 9.62 | 5/23/2000 14:25 | 5/13/2000 23:26 | 353 | 105 | 715 | 266 | 1202 | 1081 | 47.2 | 1.90E + 31 |
| 9.07 | 5/23/2000 17:02 | 5/14/2000 15:26 | 246 | 55 | 683 | 563 | 807 | 786 | 12.7 | 7.00E + 30 |
| 4.32 | 6/8/2000 9:10 | 6/4/2000 1:31 | 142 | 50 | 399 | 363 | 439 | 517 | 5.5 | 9.60E + 29 |
| 0.25 | 6/11/2000 8:01 | 6/11/2000 2:08 | 265 | 29 | 243 | 240 | 246 | 251 | 0.2 | 3.90E + 29 |
| 0.76 | 6/12/2000 22:08 | 6/12/2000 3:54 | 322 | 71 | 298 | 332 | 262 | 207 | 92.9 | 4.70E + 29 |
| 8.18 | 6/23/2000 13:03 | 6/15/2000 8:50 | 255 | 49 | 940 | 812 | 1079 | 1010 | 15.4 | 5.10E + 30 |
| 0.17 | 7/10/2000 6:38 | 7/10/2000 2:26 | 285 | 12 | 610 | 597 | 624 | 703 | 5.9 | 2.10E + 29 |
| 7.42 | 7/19/2000 15:27 | 7/12/2000 5:26 | 268 | 47 | 445 | 396 | 498 | 597 | 8.3 | 4.20E + 29 |
| 5.8 | 7/23/2000 10:41 | 7/17/2000 15:30 | 127 | 30 | 325 | 327 | 323 | 317 | 90.3 | 2.10E + 29 |
| 3.06 | 7/26/2000 18:57 | 7/23/2000 17:30 | 14 | 96 | 329 | 33 | 654 | 820 | 28.6 | 2.10E + 30 |
| 4.54 | 7/28/2000 6:34 | 7/23/2000 17:30 | 14 | 96 | 329 | 33 | 654 | 820 | 28.6 | 2.10E + 30 |
| 5.35 | 8/10/2000 5:01 | 8/4/2000 20:33 | 173 | 123 | 267 | 228 | 308 | 308 | 1.8 | 1.00E + 30 |
| 2.45 | 9/6/2000 17:00 | 9/4/2000 6:06 | 327 | 145 | 849 | 773 | 927 | 879 | 7.6 | 1.90E + 31 |
| 4.53 | 9/18/2000 14:43 | 9/14/2000 2:06 | 126 | 69 | 596 | 709 | 473 | 522 | 910 | 1.00E + 30 |
| 4.45 | 10/3/2000 0:54 | 9/28/2000 14:06 | 203 | 14 | 353 | 291 | 416 | 542 | 8.8 | 8.90E + 28 |

**Table 1** continued

| Interval[a] | SSC time | CME time | PA | Width | LS | IS | FS | S20 | Accl | E |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.21 | 10/5/2000 3:26 | 10/4/2000 22:26 | 254 | 51 | 446 | 467 | 426 | 372 | 93.5 | 4.30E + 29 |
| 3.06 | 10/28/2000 9:54 | 10/25/2000 8:26 | Halo | 360 | 770 | 605 | 948 | 885 | 17.4 | 5.10E + 31 |
| 8.47 | 11/4/2000 2:21 | 10/26/2000 15:06 | 285 | 11 | 737 | 799 | 675 | 357 | 922 | 1.40E + 29 |
| 0.49 | 11/6/2000 9:47 | 11/5/2000 22:06 | 200 | 36 | 209 | 204 | 214 | 227 | 0.4 | 1.20E + 29 |
| 5.93 | 11/10/2000 6:28 | 11/4/2000 8:06 | 2 | 83 | 341 | 0 | 677 | 808 | 29.8 | 3.50E + 29 |
| 7.75 | 11/26/2000 7:58 | 11/18/2000 13:54 | 74 | 120 | 553 | 332 | 781 | 706 | 16.2 | 6.90E + 30 |
| 3.58 | 11/28/2000 5:31 | 11/24/2000 15:30 | Halo | 360 | 1245 | 1269 | 1219 | 1238 | 93.3 | 1.10E + 32 |
| 4.44 | 12/3/2000 4:09 | 11/28/2000 17:30 | 222 | 31 | 617 | 606 | 629 | 632 | 1.3 | 1.90E + 30 |
| 3.98 | 12/22/2000 19:25 | 12/18/2000 19:54 | 195 | 62 | 230 | 216 | 246 | 319 | 2.3 | 6.30E + 29 |
| 4.11 | 1/31/2001 8:05 | 1/27/2001 5:30 | 310 | 17 | 295 | 217 | 380 | 507 | 8.8 | 6.60E + 28 |
| 9.51 | 2/12/2001 16:13 | 2/3/2001 3:54 | 95 | 56 | 271 | 198 | 347 | 376 | 4.5 | 1.20E + 29 |
| 3.18 | 3/27/2001 17:47 | 3/24/2001 13:27 | 209 | 34 | 214 | 142 | 295 | 357 | 4.5 | 1.90E + 29 |
| 5.95 | 4/4/2001 14:55 | 3/29/2001 16:06 | 267 | 33 | 441 | 418 | 467 | 470 | 1.9 | 7.30E + 28 |
| 0.44 | 4/8/2001 11:01 | 4/8/2001 0:29 | 134 | 79 | 359 | 295 | 427 | 523 | 7.6 | 4.50E + 29 |
| 4.76 | 4/11/2001 13:43 | 4/6/2001 19:30 | Halo | 360 | 1270 | 1614 | 914 | 1215 | 957 | 6.80E + 31 |
| 5.93 | 4/11/2001 15:19 | 4/5/2001 17:06 | Halo | 360 | 1390 | 1503 | 1278 | 1341 | 922 | 8.50E + 31 |
| 3.09 | 4/13/2001 7:34 | 4/10/2001 5:30 | Halo | 360 | 2411 | 1947 | 2876 | 2974 | 212 | 2.60E + 32 |
| 7.8 | 4/18/2001 0:46 | 4/10/2001 5:30 | Halo | 360 | 2411 | 1947 | 2876 | 2974 | 212 | 2.60E + 32 |
| 0.29 | 4/21/2001 16:01 | 4/21/2001 9:05 | 190 | 22 | 616 | 627 | 604 | 609 | 91 | 3.90E + 30 |
| 0.19 | 4/28/2001 5:00 | 4/28/2001 0:30 | 160 | 32 | 270 | 224 | 316 | 310 | 2.3 | 9.00E + 28 |
| 1.9 | 5/27/2001 14:59 | 5/25/2001 17:26 | 90 | 208 | 930 | 900 | 962 | 947 | 3.7 | 2.50E + 31 |
| 3.1 | 6/18/2001 2:59 | 6/15/2001 0:30 | 207 | 74 | 633 | 823 | 445 | 447 | 920 | 3.30E + 30 |
| 1.6 | 8/12/2001 11:35 | 8/10/2001 21:08 | 45 | 9 | 548 | 322 | 780 | 1218 | 58.6 | 2.30E + 29 |
| 3.86 | 8/17/2001 11:03 | 8/13/2001 14:30 | 268 | 114 | 332 | 398 | 260 | 58 | 96.5 | 1.40E + 30 |
| 3.33 | 8/27/2001 19:52 | 8/24/2001 11:50 | 155 | 11 | 805 | 853 | 762 | 649 | 914 | 1.10E + 30 |

**Table 1** continued

| Interval[a] | SSC time | CME time | PA | Width | LS | IS | FS | S20 | Accl | E |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.18 | 8/30/2001 14:11 | 8/30/2001 9:50 | 129 | 86 | 462 | 344 | 593 | 578 | 8.8 | 3.70E + 30 |
| 3.63 | 9/13/2001 2:33 | 9/9/2001 11:30 | 233 | 67 | 308 | 247 | 368 | 623 | 13.4 | 3.00E + 29 |
| 4.47 | 9/14/2001 2:05 | 9/9/2001 14:54 | 98 | 143 | 967 | 1007 | 925 | 909 | 98.1 | 1.20E + 31 |
| 1.41 | 9/25/2001 20:25 | 9/24/2001 10:30 | Halo | 360 | 2402 | 2234 | 2580 | 2500 | 54.1 | 6.50E + 32 |
| 3.24 | 9/29/2001 9:40 | 9/26/2001 3:52 | 293 | 97 | 644 | 722 | 561 | 615 | 96.3 | 7.20E + 31 |
| 6.37 | 9/30/2001 19:24 | 9/24/2001 10:30 | Halo | 360 | 2402 | 2234 | 2580 | 2500 | 54.1 | 6.50E + 32 |
| 4.7 | 10/28/2001 3:19 | 10/23/2001 10:26 | 135 | 41 | 87 | 0 | 222 | 559 | 13.4 | 2.80E + 28 |
| 8.88 | 11/15/2001 15:09 | 11/6/2001 18:00 | 28 | 26 | 315 | 322 | 307 | 233 | 92.1 | 8.80E + 28 |
| 5.99 | 11/19/2001 18:15 | 11/13/2001 18:26 | 57 | 44 | 272 | 102 | 439 | 875 | 31.6 | 2.40E + 29 |
| 4.89 | 12/23/2001 23:16 | 12/19/2001 1:54 | 180 | 5 | 411 | 349 | 476 | 488 | 4.8 | 3.20E + 28 |
| 4.63 | 12/29/2001 5:38 | 12/24/2001 14:30 | 87 | 49 | 963 | 1040 | 881 | 865 | 916 | 2.10E + 31 |
| 6.59 | 12/30/2001 20:09 | 12/24/2001 6:06 | 258 | 13 | 395 | 426 | 363 | 344 | 92.6 | 1.20E + 29 |
| 0.36 | 1/31/2002 21:27 | 1/31/2002 12:54 | 19 | 41 | 488 | 295 | 686 | 1239 | 60.3 | 3.20E + 29 |
| 4.48 | 2/17/2002 2:55 | 2/12/2002 15:30 | 65 | 118 | 448 | 397 | 502 | 508 | 4.3 | 6.20E + 30 |
| 1.04 | 2/28/2002 4:51 | 2/27/2002 3:54 | 257 | 79 | 415 | 340 | 499 | 848 | 25.2 | 2.60E + 30 |
| 3.31 | 3/20/2002 13:28 | 3/17/2002 6:06 | 159 | 21 | 632 | 685 | 577 | 565 | 96.3 | 2.30E + 29 |
| 4.34 | 3/29/2002 22:37 | 3/25/2002 14:30 | 348 | 53 | 219 | 172 | 265 | 313 | 2.9 | 6.20E + 29 |
| 3.96 | 4/14/2002 12:34 | 4/10/2002 13:27 | 340 | 159 | 650 | 540 | 759 | 876 | 21.2 | 4.90E + 30 |
| 6.14 | 4/17/2002 11:07 | 4/11/2002 7:50 | 126 | 47 | 318 | 333 | 303 | 226 | 92.5 | 8.10E + 29 |
| 5.03 | 4/19/2002 8:35 | 4/14/2002 7:50 | 323 | 76 | 757 | 812 | 700 | 709 | 96.5 | 8.00E + 30 |
| 4.53 | 4/23/2002 4:48 | 4/18/2002 16:06 | 247 | 85 | 804 | 704 | 912 | 883 | 12.3 | 1.90E + 31 |
| 3.96 | 5/10/2002 11:23 | 5/6/2002 12:26 | 88 | 17 | 193 | 193 | 193 | 196 | 0 | 1.60E + 28 |
| 5.18 | 5/11/2002 10:14 | 5/6/2002 5:50 | 112 | 69 | 226 | 200 | 253 | 379 | 4.4 | 1.10E + 29 |
| 6.49 | 5/18/2002 20:08 | 5/12/2002 8:26 | 214 | 59 | 506 | 509 | 504 | 500 | 90.4 | 1.90E + 30 |
| 4.34 | 5/21/2002 22:03 | 5/17/2002 13:50 | 89 | 16 | 552 | 499 | 603 | 789 | 15.5 | 5.00E + 29 |

**Table 1** continued

| Interval[a] | SSC time | CME time | PA | Width | LS | IS | FS | S20 | Accl | E |
|---|---|---|---|---|---|---|---|---|---|---|
| 5.59 | 5/30/2002 2:04 | 5/24/2002 11:50 | 215 | 38 | 268 | 187 | 347 | 749 | 21.9 | 2.20E + 29 |
| 4.12 | 6/1/2002 16:44 | 5/28/2002 13:50 | 232 | 17 | 643 | 587 | 697 | 863 | 16.8 | 2.50E + 29 |
| 8.34 | 6/8/2002 11:40 | 5/31/2002 3:26 | 301 | 101 | 341 | 388 | 293 | 55 | 96.1 | 2.70E + 30 |
| 8.36 | 7/17/2002 16:04 | 7/9/2002 7:31 | 116 | 14 | 523 | 549 | 499 | 430 | 95 | 1.60E + 29 |
| 0.25 | 7/25/2002 13:36 | 7/25/2002 7:32 | 277 | 32 | 340 | 329 | 350 | 378 | 1.9 | 5.60E + 29 |
| 3.74 | 7/29/2002 13:21 | 7/25/2002 19:31 | 272 | 29 | 556 | 572 | 539 | 516 | 93 | 1.90E + 30 |
| 5.29 | 8/1/2002 5:10 | 7/26/2002 22:06 | Halo | 360 | 818 | 820 | 816 | 817 | 90.1 | 3.50E + 31 |
| 2.61 | 8/26/2002 11:31 | 8/23/2002 20:50 | 262 | 131 | 861 | 1041 | 665 | 817 | 922 | 1.90E + 31 |
| 4.29 | 9/7/2002 16:36 | 9/3/2002 9:40 | 259 | 42 | 447 | 524 | 366 | 313 | 97.3 | 9.30E + 29 |
| 9.51 | 9/30/2002 8:15 | 9/20/2002 20:06 | 213 | 77 | 738 | 738 | 739 | 739 | 0.1 | 1.50E + 30 |
| 4.9 | 11/9/2002 18:49 | 11/4/2002 21:08 | 142 | 70 | 352 | 321 | 383 | 468 | 5.3 | 1.90E + 30 |
| 9.69 | 11/20/2002 11:08 | 11/10/2002 18:30 | 300 | 25 | 512 | 271 | 727 | 1521 | 106 | 1.40E + 29 |
| 4.35 | 11/26/2002 21:50 | 11/22/2002 13:27 | 133 | 24 | 514 | 614 | 413 | 80 | 917 | 1.30E + 30 |
| 3.07 | 12/22/2002 10:29 | 12/19/2002 8:54 | Halo | 360 | 433 | 519 | 333 | 368 | 95.9 | 1.80E + 29 |
| 3.59 | 3/20/2003 4:44 | 3/16/2003 14:30 | 236 | 24 | 619 | 610 | 627 | 634 | 1.3 | 6.00E + 29 |
| 2.8 | 4/8/2003 1:11 | 4/5/2003 6:06 | 204 | 14 | 459 | 408 | 512 | 478 | 2.6 | 1.40E + 28 |
| 2.69 | 5/5/2003 5:04 | 5/2/2003 12:26 | 222 | 41 | 595 | 750 | 433 | 472 | 915 | 3.90E + 29 |
| 7.95 | 6/18/2003 5:12 | 6/10/2003 6:30 | Halo | 360 | 525 | 555 | 496 | 499 | 92.7 | 1.30E + 31 |
| 0.74 | 8/17/2003 14:21 | 8/16/2003 20:29 | 246 | 60 | 565 | 588 | 543 | 496 | 94.2 | 7.90E + 26 |
| 4.81 | 10/24/2003 15:24 | 10/19/2003 19:52 | 104 | 113 | 799 | 626 | 965 | 1090 | 34.5 | 4.20E + 30 |
| 4.92 | 10/26/2003 19:08 | 10/21/2003 20:58 | 108 | 75 | 602 | 305 | 895 | 1050 | 44.2 | 1.20E + 31 |
| 9.09 | 10/28/2003 2:06 | 10/18/2003 23:55 | 98 | 114 | 544 | 521 | 569 | 566 | 2.3 | 8.80E + 30 |
| 8.1 | 10/29/2003 6:11 | 10/21/2003 3:54 | Halo | 360 | 1484 | 2014 | 923 | 1059 | 9124.3 | 1.30E + 32 |
| 2.3 | 11/4/2003 6:25 | 11/1/2003 23:06 | 254 | 93 | 899 | 1112 | 676 | 802 | 926 | 3.60E + 31 |
| 9.9 | 1/6/2004 19:51 | 12/27/2003 22:20 | 56 | 15 | 600 | 539 | 658 | 680 | 7.3 | 3.50E + 29 |

**Table 1** continued

| Interval[a] | SSC time | CME time | PA | Width | LS | IS | FS | S20 | Accl | E |
|---|---|---|---|---|---|---|---|---|---|---|
| 8.59 | 1/22/2004 1:37 | 1/13/2004 11:30 | 177 | 88 | 538 | 364 | 735 | 819 | 22.6 | 1.20E + 28 |
| 0.24 | 4/3/2004 9:47 | 4/3/2004 4:00 | 250 | 41 | 341 | 353 | 328 | 308 | 91.3 | 3.40E + 28 |
| 5.34 | 4/3/2004 14:10 | 3/29/2004 6:00 | 120 | 15 | 528 | 561 | 493 | 476 | 93.9 | 6.20E + 28 |
| 7.19 | 4/9/2004 2:33 | 4/1/2004 22:00 | 59 | 79 | 460 | 325 | 613 | 528 | 7.1 | 3.70E + 30 |
| 2.91 | 4/12/2004 18:17 | 4/9/2004 20:30 | 227 | 273 | 977 | 1000 | 955 | 959 | 93.3 | 4.30E + 30 |
| 6.25 | 4/26/2004 16:03 | 4/20/2004 10:08 | 296 | 98 | 248 | 176 | 323 | 296 | 2.3 | 6.70E + 29 |
| 5.31 | 7/16/2004 21:55 | 7/11/2004 14:30 | 37 | 39 | 470 | 326 | 614 | 784 | 21.4 | 4.60E + 28 |
| 4.36 | 7/22/2004 10:36 | 7/18/2004 1:54 | 231 | 10 | 541 | 371 | 708 | 1134 | 49.2 | 1.50E + 28 |
| 3.34 | 7/24/2004 6:14 | 7/20/2004 22:06 | 149 | 43 | 470 | 450 | 492 | 571 | 5.3 | 4.70E + 28 |
| 4.86 | 7/30/2004 21:14 | 7/26/2004 0:30 | 217 | 64 | 474 | 349 | 598 | 676 | 13.7 | 4.80E + 29 |
| 0.32 | 8/29/2004 10:04 | 8/29/2004 2:30 | 274 | 29 | 1195 | 1340 | 1044 | 849 | 946 | 5.00E + 29 |
| 0.22 | 10/27/2004 12:12 | 10/27/2004 6:54 | 82 | 16 | 281 | 207 | 362 | 1029 | 43.2 | 1.20E + 28 |
| 1.08 | 11/9/2004 9:30 | 11/8/2004 7:31 | 242 | 19 | 213 | 209 | 217 | 239 | 0.6 | 5.10E + 28 |
| 7.1 | 12/5/2004 7:46 | 11/28/2004 5:26 | 65 | 23 | 425 | 395 | 457 | 504 | 4.1 | 2.40E + 29 |
| 3.34 | 12/11/2004 13:40 | 12/8/2004 5:26 | 163 | 7 | 561 | 498 | 628 | 1227 | 54.1 | 2.50E + 28 |
| 6.03 | 12/30/2004 6:23 | 12/24/2004 5:36 | 291 | 92 | 779 | 614 | 961 | 1336 | 58 | 4.10E + 30 |

PA: is the CME position angle (°), Width: is the CME angular width (°), Ls: CME linear velocity (km/s), Is: CME initial velocity (km/s), FS: CME final velocity (km/s), S20: CME velocity at distance of 20Rs (km/s), Accl.: CME acceleration ($m/s^2$), *E* CME energy (erg)

[a] Interval: Time interval of the arriving of ICME shock to the magnetosphere (days)

## 4.2 Estimated Error

Figure 3 shows a histogram of computed error in the arrival time of the prediction curve in Fig. 2. The error is defined as the deviation from the prediction curve for each of the measured travel times in Table 1. It is observed from Fig. 3, that our model has a lower average estimated error (5.3 h). Goplaswamy et al. (2001a) found the mean value of this error is within of 10.7 h.

The differences between this result and that obtained by Gopalswamy et al. (2000a, 2001a), may be owed to the model of Gopalswamy et al. (2000a, 2001a) predicted the arrival time of ICME ejecta to the near- Earth orbit using Newton's low of ICME motions while our model is concerned with the prediction of the ICME shocks from the sun until the ICME shock reaches

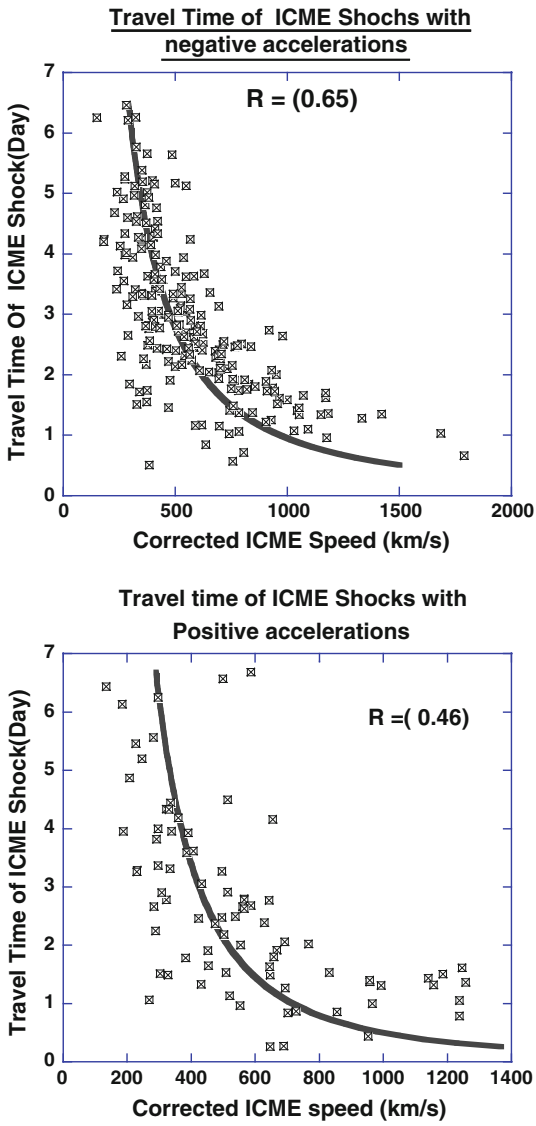


**Fig. 4** The travel time of ICMEs shocks for both negative (*above*) and positive accelerations (*below*)

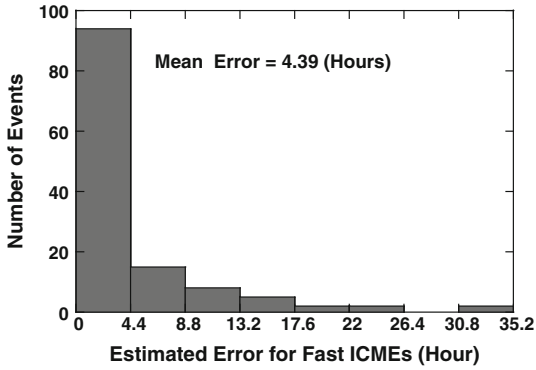


**Fig. 5** Histogram of estimated error for fast ICMEs

the Earth's magnetosphere not the near -Earth orbit as the Gopalswamy et al. (2000a, 2001a), followed the ICME ejecta. Or may be owed to the 3-D structure of the ICME shocks used in our model are more wider than those of ICME ejecta used by Gopalswamy et al. 2001a). Otherwise may be due to the differences in the periods and the number of events in each study.

### 4.3 The Accelerated and Decelerated ICME Shocks

In this section we separated the ICME shock events into two groups according to their effective acceleration and deceleration. From Fig. 4 we showed that the faster ICMEs (with negative acceleration are decelerated by solar wind plasma) are more correlated to their associated travel times than ICMEs with positive acceleration. The fractional error bars of fast ICME shocks is found to be equal to 4.39 h as shown from Fig. 5.

This result could be interpreted by the fact that the fast ICME shocks reach the Earth's magnetosphere in shorter time than the slow ICME shocks. Consequently, the errors in the travel time of the fast ICME shocks are less than those for the slow events.

## 5 Conclusions

In the present paper, the relation between the near-Earth ICME shocks and their associated ICMEs observed near-Sun by SOHO/LASCO coronagraph have been studied during the 23rd solar cycle.

According to this study, we obtained an empirical equation between the travel times, $T_C$ of the ICME shocks and their associated corrected CME Velocities $V_{CME}$, from which we can predict the value of $T_C$ if we know the value of $V_{CME}$. Also we found that there is a good correspondence between the travel time of the ICMEs shocks and their associated radial speeds. In addition we have separated the ICME shocks into two sets according to their effective acceleration and deceleration. The results showed that the faster ICME shocks (with negative accelerations) are more connected to their associated travel times than those with positive accelerations.

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