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A statistical study on the stand-off distances of interplanetary coronal mass ejections

A. Mujiber Rahman [a,*], A. Shanmugaraju [b], S. Umapathy [a], Y.-J. Moon [c]

[a] School of Physics, Madurai Kamaraj University, Madurai, Tamilnadu 625021, India
[b] Department of Physics, Arul Anandhar College, Karumathur, Tamilnadu 625514, India
[c] School of Space Research, Kyung Hee University, Yongin 446-701, Republic of Korea

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ABSTRACT

We have analyzed the stand-off distance values of 101 interplanetary CMEs (ICMEs) observed during the period 1997–2005. Main aim of the present work is to study the stand-off distance and its dependence on various parameters of CMEs, ICMEs and IP shocks, Alfvenic Mach numbers and transit time. From the distribution, the stand-off time and stand-off distance values of many of the events are found to be in the range between ~2–20 h and ~1–40 $R_\odot$ ($R_\odot$ = Solar radius). From the correlation between speed of CMEs and stand-off distance, we noted smaller stand-off distance for energetic CMEs, which indicated that the driver CME (CME which is generating the shock) and its shock travel closely together. From the correlation plot between CME acceleration and stand-off distance, we found that the highly decelerated events and highly accelerated events have lower stand-off distance range (i.e., 10–40 $R_\odot$) than the other events. The events with longer travel time to reach 1 AU (> 70 h) show stand-off times ≤ 20 h and for those faster events ($V_{CME} > 2200$ km/s) with smaller travel time (≤ 40 h), stand-off time is extremely low (≤ 10 h). A wide range of stand-off distance is seen for a particular value of CME and ICME parameters. The poor correlations of stand-off distance with all the above parameters confirm that the stand-off distance does not strongly depend on CME, ICME and IP shock parameters, but depends on a combination of all these parameters. On the other hand, the faster CMEs having lower stand-off distance and/or stand-off time imply that as long as the CMEs are energetic, the CMEs and shocks travel closely together. Also, it can be noted that the stand-off distance is not only dependent on gamma, but it is related to other parameters.

1. Introduction

It is well established that coronal mass ejections (CMEs) are complex events involving the release of large amounts of material, energy, and magnetic field from the Sun into the solar wind. Once ejected CMEs travel through the solar wind and interact with it, often setting up fast-mode MHD shocks, which in turn accelerate charged particles to very high energies (Gopalswamy et al., 2009). Since the solar wind is made up of steady and turbulent flows, discontinuities, shocks and also CMEs tend to locally adopt to ambient (i.e., background) solar wind (e.g., Gosling and Riley, 1996; Gopalswamy et al., 2000). These are likely to contribute significant change on the propagation of the CME. CMEs in the interplanetary medium are known as interplanetary CMEs or ICMEs for short. The interplanetary (IP) shocks move very fast (~450 to 2500 km/s) and are observed mainly as discontinuities in the density. It has been found that a CME's full kinematic evolution may undergo three distinct phases: an initiation phase of slow rising, a major acceleration phase of fast velocity increasing, and finally a propagation phase with minor velocity change (Zhang et al., 2001). The first two phases mainly occur in the inner corona (i.e., $< 2.0\ R_\odot$), while the third phase is largely observed in the outer corona (i.e., $> 2.0\ R_\odot$) by traditional white light coronagraphs.

CMEs arrive at the Earth with or without shocks, but those with shocks are generally more energetic (see e.g., Tsurutani et al., 1988; Gopalswamy et al., 2008). If the solar wind plasma is swept up faster than the Alfven speed, a fast mode MHD shock forms at a distance known as the stand-off distance determined by the geometry of the driving CME and the upstream Alfvenic Mach number (Gopalswamy et al., 2005). There are not many studies especially on stand-off distance except a few. For example, Gopalswamy and Yashiro (2011) measured the stand-off distance at the shock nose, where the magnetic field of the ambient medium was expected to be substantially radial and hence the shock quasi-parallel. Stand-off distance of CME-driven shocks have

* Correspondence to: Department of Physics, Hajee Karutha Rowther Howdia College, Uthamapalayam, Tamilnadu 625533, India. Tel.: +91 9443926682.
E-mail address: mujib73@gmail.com (A. Mujiber Rahman).

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been investigated from an in-situ perspective by a few authors (see, e.g., Russell and Mulligan, 2002; Manchester et al., 2004; Odstrcil et al., 2005; Lepping et al., 2008; Zhang et al., 2008). Russell and Mulligan (2002) found that the shock stand-off distance (i.e., thickness of magnetosheath) was of the order of 21 $R_\odot$ at 1 AU for a single event. Lepping et al. (2008) derived an average stand-off distance of about 8 $R_\odot$ at 1 AU for 29 events during the period 1996–2006.

Zhang et al. (2008) studied statistically the sizes of 46 interplanetary coronal mass ejections (ICMEs) and the preceding shock sheath regions in near-Earth space during 1996–2005. The 46 events studied were a subset of the events responsible for intense ($Dst \leq -100$ nT) geomagnetic storms in which only a single ICME was responsible for generating the storm. They found that the durations and radial sizes of these ICMEs range from 8.0 to 62.0 h and 0.08 to 0.63 AU, respectively, with average values of 30.6 h and 0.37 AU. On the other hand, the sheath durations and radial sizes range from 2.6 to 24.5 h and 0.03 to 0.31 AU, with average values of 10.6 h and 0.13 AU.

Farris and Russell (1994) emphasized the importance of the radius of curvature and not the radius from some arbitrary “center” of an obstacle in determining the stand-off distance. Using the results of Landau and Liftshitz (1959) and Spreiter et al. (1966), they explained that the distance of the shock was dependent upon the size of the obstacle, the ratio of specific heats, and the upstream Mach number. As noted by, Farris and Russell (1994), the dependence of the bow shock position on the size of the obstacle is a proportional relationship. Yermolaev et al. (2009) compiled a catalog of large-scale phenomena in the solar wind over the observation period of 1976–2000 using the measurement data presented in the OMNI database. They identified different types such as, heliospheric current sheet, co-rotating interaction regions, ICMEs, sheath, etc. and studied their characteristics. In addition, Yermolaev et al. (2010), selection of ICME (Magnetic Cloud and Ejecta) types was carried out and it was shown that sheath width depends on ICME type (16 h for sheath before Ejecta and 9 h before MC). Hence, they stressed the importance of ICME type in the investigations of sheath width. Eselevich and Eselevich (2011) also studied the generation of shock discontinuities excited by CMEs in the corona and found that the effective ratio of specific heats varies from 2 to 5/3. They also studied the dependence of Alfven Mach number on the shock discontinuity in the coronal shocks and interplanetary shocks and concluded that discontinuities preceding CMEs are collisionless shocks.

Manoharan and Mujiber Rahman (2011) correlated the stand-off time with CME travel time and found that events with longer travel time to reach 1 AU (i.e., ≥ 70 h) have lesser stand-off times (≤ 20 h). However, the scatter in the stand-off time with respect to the travel time was large and so they suggested the need for more investigations. This is the motivation for the present work. The main objective of the present work is to study the stand-off distance for 101 events and to correlate them with parameters of CMEs, ICMEs, IP shocks. This paper is organized as follows: Section 2 deals with data selection and important results obtained from the study are discussed in Section 3. In Section 4, a summary of the results is presented.

2. Data selection

In the present work, we considered a set of 101 earth-directed CME events from the list given by Mujiber Rahman et al. (2012), associated with ICMEs and interplanetary shocks observed during the period 1997–2005. This list of halo and partial halo CMEs provides a good sample of events, covering a wide range of speed ($\sim$100–3200 km/s) in the LASCO field of view. In our earlier work, we analyzed the interplanetary parameters of CMEs with and without type II bursts. But in the present study, our objective is to find the correlation of stand-off distance with interplanetary parameters such as speeds of ICMEs and IP shocks, Mach numbers (both Alfvenic and magnetosonic), Shock transit time and acceleration. Among the 101 CME events the first 91 CME events were obtained from the list given by Manoharan et al. (2004) and the next 10 events were selected from the LASCO CME list (http://cdaw.gsfc.nasa.gov/CME_list/) according to the criteria used by Manoharan et al. (2004) and the speed of CMEs should be greater than 2200 km/s.

We considered the shock wave disturbances detected by the Wind spacecraft during 1997–2005 (available at http://www-spof.gsfc.nasa.gov/wind), supplemented with the shock lists obtained from Proton Monitor (PM) instrument on board SOHO mission (available at http://umtof.bartol.udel.edu/ace). By examining solar wind plasma data (from Solar Wind Experiment (Wind/SWE) instrument, available at http://web.mit.edu/space/www/wind) and interplanetary magnetic field data (from Magnetic Field Investigation (Wind/MFI) instrument, available at http://lepmfi.gsfc.nasa.gov/mfi), we identified 101 IP shocks and their associated interplanetary CMEs (ICMEs). Solar wind parameters associated with the shocks and CME at the near Earth spacecraft were obtained from the available online data using the website (http://nssdc.gsfc.nasa.gov/omniweb). For each event, we found the shock onset date, time, shock speed, Mach numbers (Alfvenic Mach number, M_a, Magnetosonic Mach number, M_s) and transit time as described below. The shocks were identified using sudden discontinuity in plasma parameters of proton density, flow speed and proton temperature as described in Manoharan et al. (2004). The shock speeds (see e.g., Douglas and Park, 1983) were calculated using density and speed from upstream and downstream of shock, $Vs = (v_1 n_1 - v_2 n_2)/(n_1 - n_2)$, v_1 and n_1 are speed and density before the shock front (upstream region), v_2 and n_2 are the speed and density after the shock front (downstream region). Alfvenic Mach (M_a) numbers (Velli and Prunetti, 1997) are calculated using magnetic field, density and velocity data at the shock front (M_a=upstream speed/Alfvenic speed) and magnetosonic Mach numbers (M_s=shock speed/fast mode speed). Transit time is represented by the time difference between the CME time in LASCO C2 image and shock time in WIND spacecraft data.

We identified the ICME associated with an IP shock by examining the solar wind plasma data (proton density, speed and temperature) as well as magnetic field measurements followed after the IP shock onset, as suggested by Manoharan et al. (2004). There is a number of plasma and magnetic field features are associated with ICMEs (i.e. interplanetary ejecta (EJ) of CMEs). However, we identified ejecta using (1) low proton temperature, (2) strong magnetic field, and (3) a smooth rotation in the magnetic field direction indicative of a magnetic cloud (MC). MCs are a subset of ejecta. For a few events, high charge state of iron has also been examined to identify the ICME plasma. The presence of these signatures singly or together varied from one ICME to the other.

In the present study, the stand-off distance is calculated as follows. The stand-off time of a CME at a distance is given by the time difference between the arrival of a CME driven shock disturbance and the CME at the given distance (see, e.g., Manoharan and Mujiber Rahman (2011), Mujiber Rahman et al. (2012)). That is, the stand-off time is referred as the time difference between the ICME and IP shock arrival time at 1 AU. The stand-off distance is calculated using stand-off time multiplied by the ICME speed (The peak flow speed during the passage of ICME relative to the instrument). By using this method we obtained stand-off distance values ranging between 0.5 $R_\odot$ and 74 $R_\odot$ at 1 AU. We have shown the plots of solar wind magnetic