Propagation of coronal mass ejections from the Sun to the Earth

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Abstract. Coronal mass ejections (CMEs), as they can inject a large amounts of mass and magnetic flux into the interplanetary space, are the primary source of space weather phenomena on the Earth. The present review first briefly introduces the solar surface signatures of the origins of CMEs and then focuses on the attempts to understand the kinematic evolution of CMEs from the Sun to the Earth. CMEs have been observed in the solar corona in white-light from a series of space missions over the last five decades. In particular, LASCO/SOHO has provided almost continuous coverage of CMEs for more than two solar cycles until today. However, the observations from LASCO suffered from projection effects and limited field-of-view (within 30 $R_\odot$ from the Sun). In 2006, the launch of the twin STEREO spacecraft has made possible multiple viewpoints imaging observations, which enabled us to assess the projection effects on CMEs. Moreover, heliospheric imagers (HIs) onboard STEREO continuously observed the large and unexplored distance gap between the Sun and the Earth. Finally, the Earth-directed CMEs that earlier have been routinely identified only near the Earth at 1 AU in situ observations from ACE and WIND, could also be identified at longitudes away from the Sun–Earth line using the in situ instruments onboard STEREO. We describe the key signatures for the identification of CMEs using in situ observations. Our review presents the frequently used methods for estimation of the kinematics of CMEs and their arrival time at 1 AU using primarily SOHO and STEREO observations. We emphasize the need of deriving the three-dimensional (3D) properties of Earth-directed CMEs from the locations away from the Sun–Earth line. The results improving the CME arrival time prediction at Earth and the open issues holding back progress are also discussed. Finally, we summarize the importance of heliospheric imaging and discuss the path forward to achieve improved space weather forecasting.

Keywords. Sun—coronal mass ejections—heliospheric imagers.

1. Introduction

The extremely hot, tenuous and outermost atmosphere of the sun is called the solar corona. This extends to several millions of kilometers above the visible surface of the Sun (i.e., solar photosphere) and is much fainter than the photosphere. The solar corona is naturally seen in visible light only during a total solar eclipse when the moon shadows the bright photosphere. The solar corona is also observable with an instrument called coronagraph which was introduced in 1931 by the French astronomer Bernard Lyot (Lyot 1939). A coronagraph creates an artificial eclipse by selectively blocking out the photospheric light from the disk of the Sun so to observe the corona.

It is now understood that the solar corona releases a constant out-stream of energized charged particles, which is called solar wind (Biermann 1951; Parker 1958). The solar wind fills the interplanetary space and its existence was first confirmed by direct observations from spacecraft Luna 1 (Gringauz et al. 1960). In addition to ubiquitous solar wind, the solar corona frequently expels large-scale magnetized plasma structures into the heliosphere. Such episodic expulsions of plasma from the Sun are called Coronal Mass Ejections (CMEs). The earliest observation of a CME probably dates back to the eclipse of 1860 as clearly seen in a drawing recorded by G. Temple. Some definite inferences for CMEs from the Sun were made before their formal detections (Chapman & Ferraro 1931; Eddy
Figure 1. An image of a ‘halo’ CME observed by LASCO-C2 coronagraph onboard SOHO. On 28 December 2000, the CME was launched from the Sun. The white circle in the center is the size and location of the solar disk, which is obscured by the coronagraph’s occulter, covering up to 1.7 $R_\odot$ (image credit: http://lasco-www.nrl.navy.mil).

However, CMEs were first detected in 1971 by a coronagraph onboard NASA’s seventh Orbiting Solar Observatory (OSO-7) satellite (Tousey 1973). The name CME was initially coined for a feature which shows an observable change in coronal structure that occurs on a time scale of few minutes to several hours and involves the appearance (and outward motion) of a new, discrete, bright, white-light feature in the coronagraphic field-of-view (FOV) (Hundhausen et al. 1984).

The observations of CMEs have been made using white-light coronagraphs, interplanetary scintillation measurements, and in situ observations. The coronagraphs record a two-dimensional (2D) image of a three-dimensional (3D) CME projected onto the plane of the sky. Therefore, the morphology of CME in coronagraphic observations depends on the location of the observing instruments (e.g., coronagraphs) and the launch direction of CME from the Sun. The CMEs launched from the Sun toward or away from the Earth, when observed by the near-Earth coronagraphs will appear as ‘halos’ surrounding the occulting disk of coronagraphs (Howard et al. 1982). Such a CME is called a ‘halo’ CME (Figure 1). An example of coronagraph observing from near Earth is Large Angle Spectrometric COronagraph (LASCO) onboard SOlar and Heliospheric Observatory (SOHO) located at the L1 point of the Sun–Earth system. A CME having $360^\circ$ apparent angular width is called ‘full halo’ and with apparent angular width $>120^\circ$ but $<360^\circ$ is called as ‘partial halo’. Such a nomenclature of a CME is restricted by its viewing perspective. The observations of solar activity on the solar disk, associated with CME, are necessary to help distinguish whether a halo CME was launched from the front-side or back-side of the Sun relative to the observer. It is important to note that among all the CMEs, only about 10% are partial halo type (i.e., width $>120^\circ$) and about 4% are full halo type (Webb et al. 2000).

The CMEs observed as front-side halo are important as they are the key link between solar eruptions and major space weather phenomena. The term space weather refers to conditions in the space between the Sun and the Earth (e.g., in the solar wind, Earth’s magnetosphere, ionosphere and thermosphere) that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health. The majority of geomagnetic storms of solar cycles 23 and 24 are known to be caused by halo CMEs, confirming the importance of the source location of CMEs (Gopalswamy 2010; Lavraud et al. 2020). The source regions of front-side halo CMEs can be studied in greater detail with instruments capable of imaging the structures at the base of the corona. The example of such instruments are Extreme-Ultraviolet Imaging Telescope (EIT) onboard SOHO, Atmospheric Imaging Assembly (AIA) onboard Solar Dynamics Observatory (SDO) and Extreme-Ultraviolet Imager (EUVI) as a part of Sun–Earth Connection Coronal and Heliospheric Investigation (SECCHI) package onboard Solar TERrestrial RElations Observatory (STEREO) (Delaboudinière et al. 1995; Howard et al. 2008; Lemen et al. 2012). If such CMEs do not get a large deflection during their interplanetary propagation, they are expected to be sampled at observer’s location by in-situ spacecraft (Webb et al. 2000). It is important to note that CMEs are the 3D structures, therefore, single-point imaging observations would suffer from the unavoidable projection effect (Burkepile et al. 2004). In the case of a halo CME, the projection effects are considerably large and the measured speed of a CME is underestimated, while its angular width is overestimated (Xie et al. 2004). The CME’s initial speed, angular width, direction, and background solar wind are known to govern the transit time of the CME from the Sun to 1 AU (Gopalswamy et al. 2000a; Möstl & Davies 2013). It is shown that even CMEs of equal speeds, but different geometry and propagation direction can take quite different transit times to reach the Earth. Therefore, the kinematic and geometric parameters of halo CMEs need further corrections for accurate forecasting of their arrival time (Shen et al. 2014). In addition to forecasting purpose, the projection effects on halo CMEs also impose limitations on our understanding of physical characteristics of CMEs.
Some CMEs observed near the Sun often appear as a ‘three-part’ structure comprising of an outer bright frontal loop (i.e., leading edge) and a darker underlying cavity within which, is embedded a brighter core as shown in Figure 2 (Illing & Hundhausen 1985). The front may contain swept-up material by erupting flux ropes or the presence of pre-existing material in the overlying fields (Illing & Hundhausen 1985; Riley et al. 2008). The cavity is a region of lower plasma density, but probably higher magnetic field strength, i.e., a manifestation of a driving flux rope (Forsyth et al. 2006). The brightest component of the three-part structure, i.e., the core of the CME can often be identified as prominence (i.e., filament) material based on their visibility in chromospheric emission lines (Bothmer & Schwenn 1998; Schmieder et al. 2002). Contrary to an established perspective held for several decades, recently, it has been shown that bright cores can be observed in many CMEs, which are not associated with filament eruptions in any way (Howard et al. 2017; Song et al. 2017). Moreover, they found that in some cases, where CMEs were associated with filament eruptions, the bright cores neither geometrically resemble eruptive filaments nor exhibit He II emission as expected from cool filament materials in the coronagraphic FoV. Based on this, Howard et al. (2017) suggested that the bright core within the cavity could be an optical illusion produced by the geometrical projection of a twisted 3D flux rope into a 2D plane or it can appear due to the natural evolution of an erupting flux rope (Howard et al. 2017).

It is noted that the frequency of occurrence of CMEs around solar maximum is ≈5 per day and at solar minimum, it is ≈4 per week (Cyr et al. 2000; Webb et al. 2012). CMEs having a three-part structure are only about 30% of all the CMEs from the Sun, yet this is considered as the ‘standard CME’ configuration in observational and theoretical studies (Gopalswamy 2004, 2006a). Despite the common association of CMEs with eruptive filaments and flux ropes, surprisingly only about 4% of the Earth-arriving ICMEs show the signatures of filaments and only about 35% of ICMEs show the signatures of flux ropes in in-situ observations at 1 AU (Lepri & Zurbuchen 2010; Richardson & Cane 2010). The absence of flux rope in some ICMEs is understood in term of geometric selection effect (Kilpua et al. 2011; Solanki et al. 2020), but the rarely observed filaments at large distances from the Sun pose a question if they survive at all beyond a few solar radii from the Sun. There are case studies that have shown that soon after the launch of a filament from the Sun, it may get fragmented into magnetic Rayleigh–Taylor (MRT) unstable plasma segments and fall back into the solar atmosphere (Innes et al. 2012; Mishra et al. 2018a, b). Joshi et al. (2013) have shown a case study where the core of a CME associated with an asymmetric filament eruption exhibited downfall of its plasma, which they explained using a self-consistent model of a magnetic flux rope. Thus, the draining of filament plasma can be partly responsible for their absence in coronagraphic and in situ observations. Also, the ionization of the filament material can take place during its evolution away from the Sun (Howard 2015), and this can make them spread out across their respective field lines and become indistinguishable from the material making up the surrounding CME.

It is known that not all CMEs appear to have a very large angular width in coronagraphic images, in fact, some CMEs appear as narrow jets. However, it should be noted that wide CMEs are not necessarily very global, but rather may have a propagation direction along the Sun-observer line, and so they appear large by perspective, as noted for the so-called halo CMEs. CME’s are classified as narrow when they have an apparent angular width <20° and they are a small subset of all CMEs (Yashiro et al. 2003). The average width of normal three-part structure CMEs has been reported to range from 50° to 70° depending on the inclusion of partial halos, full halos and different phases of a solar cycle (Cyr et al. 2000; Webb et al. 2012). Based on the LASCO CMEs in the CDAW catalog (Gopalswamy et al. 2010), narrow CMEs are found to be only about 12% and 22% of the total number of CMEs during the minimum and maximum of solar cycle 23, respectively (Yashiro et al. 2003). According to Gilbert et al. (2001), the average speeds of narrow CMEs are similar to that of normal CMEs. The speeds of narrow CMEs near the Sun range from few km s⁻¹ to 1150 km s⁻¹, but...
for the normal CMEs, it can range from few km \( s^{-1} \) to 3000 km \( s^{-1} \) (Cyr et al. 2000). On the other hand, Yashiro et al. (2003) found that narrow CMEs tend to be faster than normal CMEs during solar maximum. The average mass of a narrow CME is less than about 10% of the mass of a normal CME, which is \( \sim 1.5 \times 10^{12} \) kg. It has been found that narrow CMEs are the outward extensions of EUV jets and they probably have different acceleration mechanisms than normal CMEs (Wang et al. 1998). Recent studies have focused on investigating the triggering mechanism and kinematics of jet-like CMEs (Solanki et al. 2019, 2020). Also, studies have reported the simultaneous launch of jet-like and bubble-like CMEs to investigate their eruption mechanisms (Shen et al. 2012; Duan et al. 2019).

The triggering and driving mechanisms of CMEs have been the subject of extensive research aimed at developing CME initiation models constrained by observations (Chen 2011). The launch of CMEs requires that the magnetic field lines must be opened by some processes to allow the plasma to escape from the Sun. The onset of CMEs has been associated with many solar disk phenomena, such as flares (Feynman & Hundhausen 1994), prominence eruptions (Hundhausen 1999), coronal dimming (Sterling & Hudson 1997), arcade formation (Hanaoka et al. 1994). In fact, it has been observed that the CMEs often show spatial and temporal relations with solar flares, eruptive prominences (Munro et al. 1979; Webb & Hundhausen 1987; Gopalswamy et al. 2003b) and with helmet streamer blowouts. Solar flares are observed as localized sudden brightening on the Sun across all wavelengths at the time scale of minutes (Aschwanden 2002; Benz 2008) and historically they were considered to be the drivers for CMEs and interplanetary shocks. Many strong CMEs are associated with intense flares, but most of the flares are ‘confined’ or ‘compact’ and occur independently of CMEs, and thus, there is no one-to-one relationship between flares and CMEs (Yashiro et al. 2008).

Based on several studies in the last two decades, it seems that CMEs and flares are part of a single magnetically-driven phenomenon, which creates a larger net energy reservoir available for both phenomena (Compagnino et al. 2017). Therefore, a unified standard flare model known as Flux Cancellation or Catastrophe model has been developed and refined over the last few decades (Forbes & Isenberg 1991; Priest & Forbes 2002). Another model called Breakout model has been developed to describe the association of CMEs with flares (Antiochos & Klimchuk 1991). Therefore, it is evident that although CMEs and flares may not be causally related, they both seem to be involved with the reconfiguration of complex magnetic field lines within the corona caused by the same underlying physical processes, e.g., magnetic reconnection (Priest & Forbes 2002; Compagnino et al. 2017).

Furthermore, the eruption of prominences is also often associated with CMEs, with the erupted material forming their bright cores. The prominences are caused by the formation of flux ropes low in the sheared magnetic structure in the corona, but they are about 100 times cooler and denser than the corona. It is established that prominences appear as bright features at the limb, but appear darker than their background on the solar disk, where they are called filaments. It is now suggested that perturbations (i.e., precursor activities) in coronal magnetic fields forming a CME begin well before any observed associated surface activity, such as flares or erupting prominences (Gopalswamy et al. 2006). Some of the CMEs are known to appear from the blowout of a helmet streamer due to dynamical evolution of arcades, flux emergence, or shearing of magnetic field lines (Vourlidas et al. 2002a; Gopalswamy 2006a). A streamer is a dense structure containing closed and open fields, which are observed by coronagraphs above the solar limb.

In the attempt to establish the association between CMEs observed in coronagraphs and their signatures at the solar surface, it has been noted that some CMEs do not have easily identifiable signatures (such as coronal dimming, coronal wave, filament eruption, flare and post-eruptive arcade) to locate their source regions on the Sun (Ma et al. 2010; Vourlidas et al. 2011). Such CMEs are called ‘problem or stealth CMEs’ (Robbrecht et al. 2009). On comparing CMEs with and without low coronal signatures, it is found that stealth CMEs are slow, typically from 100 to 300 km \( s^{-1} \) having gradual acceleration and their source regions are usually located in the quiet Sun in proximity with coronal holes rather than active regions (Ma et al. 2010; Nitta & Mulligan 2017). Some stealth CMEs are found to be narrow, but they can be wide enough to show the typical three-part structure of the CME. It was suggested by D’Huys et al. (2014) that the physical process, such as reconnection that enables the stealth CMEs, probably occurs at higher altitude. They found that in most of the cases a stealth CME was preceded by another nearby CME, which might have destabilized the coronal magnetic field making a path for the stealth CME. The modeling of stealth CMEs by Lynch et al. (2016) confirmed the results of Howard & Harrison (2013) that there is no fundamental difference between stealth CMEs and most of the slow streamer blowout CMEs. The initiation mechanism and geoeffectiveness of stealth CMEs associated
with the eruption of coronal plasma channel and jet-like structures have also been studied recently (Mishra & Srivastava 2019).

The important lesson from earlier studies on the origin of CMEs is that although the physical processes making the eruption of CMEs differ in different models, the overall idea is essentially the same: a magnetic field configuration initially kept in equilibrium needs to be disturbed somehow to make the system erupt. One possibility is that the initial configuration may have an underlying sheared magnetic field (often called core) held down by an overlying field and the equilibrium can be disrupted by the magnetic reconnection between the sheared magnetic core and the overlying field. This can lead to the reconfiguration of magnetic field lines causing eruptions beyond the overlying fields (Antiochos & Klimchuk 1991). There also exists a scenario of accumulating twist in the magnetic core leading to kink instability, which can push aside the overlying field and make eruption possible (Török & Kliem 2005). Once the eruption of a CME has taken place, then the remaining magnetic field eventually closes, probably via some form of large-scale magnetic reconnection. It is noted that despite the development in understanding the origin of CMEs, the models are inadequate to completely match observations of an evolving CME under pressure, magnetic and gravitational forces (Gopalswamy 2004; Webb et al. 2012).

CMEs can lead to disturbances in the heliosphere, from their birth-place in the corona up to several AU distances away from the Sun, e.g., interplanetary shocks, radio bursts, intense geomagnetic storm, large solar energetic particles (SEPs) events and Forbush decreases (FDs) (Kahler et al. 1978; Gosling 1993; Gopalswamy et al. 2000b; Wang et al. 2000; Gopalswamy 2006b; Richardson & Cane 2010; Wiedenbeck et al. 2020). It is shown that SEP events are associated with fast and wide CMEs near the Sun (Gopalswamy et al. 2003a). The accelerated electrons by CME-driven shocks can produce Type II radio bursts that appear as slowly drifting features in radio dynamic spectra (Gopalswamy et al. 2013). The distance of CME from the Sun at the time of onset of type II bursts is the height where the CME becomes super-Alfvénic to drive fast mode MHD shocks. The height of shock formation is important in understanding the SEPs and their charge states. The studies on shock formation height suggest that shocks related to metric and decameter–hectometric (DH) type II bursts form at heights smaller and larger than 2 $R_\odot$ from the center of the Sun, respectively (Ramesh et al. 2012; Gopalswamy et al. 2013). Studies using extreme ultra-violet and white-light imaging observations of CMEs have suggested that the type II bursts can originate from anywhere on the shock front (i.e., at the nose or flanks) depending on which location is favorable for electron acceleration. The pre- and post-shock parameters of coronal plasma were studied by Bemporad & Mancuso (2010) and they found an increase in plasma temperature and magnetic field across the shock. The effects of shock compression have also been noted in the in-situ observations at 1 AU in the scenario, where the following shocks penetrated through preceding ICMEs (Harrison et al. 2012; Liu et al. 2012; Mishra & Srivastava 2014).

CMEs and their driven shocks are found to interact with the atmosphere and magnetosphere of planets leading to severe space weather activity (Wang et al. 2003; Schwenn 2006; Baker 2009; Mishra et al. 2015a; Luhmann et al. 2020). A typical example of a space weather event is the geomagnetic storm in which a major disturbance of Earth’s magnetosphere takes place due to the efficient transfer of energy from the solar wind into the space environment surrounding the Earth. The effect of CMEs on a planet is governed by the magnetic nature of the planet. The Earth has a magnetic field and hence, Earth-arriving ICME structures having strong southward magnetic field component ($B_z$) interact with the Earth’s magnetosphere at the day-side magnetopause. In this interaction, solar wind energy is transferred to the magnetosphere, primarily via magnetic reconnection that produces non-recurrent geomagnetic storms (Dungey 1961; Tsurutani et al. 1988; Gonzalez et al. 1994; Baker 2009). It has been shown that 83% intense geomagnetic storms are due to CMEs (Zhang et al. 2007). Few of the intense storms may occur because of corotating interaction regions (CIRs). CIRs form when the fast speed solar wind overtakes the slow speed solar wind ahead and leads to the formation of an interface region that has increased temperature, density and magnetic field. The arrival time of interacting CMEs and their geomagnetic consequences have also been studied extensively (Farrugia et al. 2006; Lugaz & Farrugia 2014; Liu et al. 2014; Mishra et al. 2015a; Lugaz et al. 2017). Thus, from a space weather perspective, it is important to estimate the arrival time and transit speeds of CMEs as well as orientation of magnetic field in the CMEs near the Earth well in advance to predict the severity of these events (Gonzalez et al. 1989; Srivastava & Venkatakrishnan 2002; Vourlidas et al. 2019).

The Earth-arriving CME-driven shock compresses the day-side Earth’s magnetosphere and causes the storm sudden commencement (SSC) (Chao & Lepping 1974). The horizontal component of Earth’s magnetic field, which can be measured by ground-based
magnetometers, is found to be increased during SSC (Dessler et al. 1960; Tsunomura 1998). Furthermore, the sheath region lying between the shock and flux rope gets compressed and may also have negative $B_z$. It is also well proven that CMEs are responsible for the periodic 11-year variation in the galactic cosmic rays (GCRs) intensity (Cane 2000). Moreover, CMEs are found to be responsible for Forbush decreases (FDs) (Forbush 1937). Non-recurrent FDs are defined as a sudden shorter-term decrease of the recorded intensity of GCRs when a CME passes the Earth. In FDs, the depression in the intensity of GCRs by 3–20% typically lasts for minutes to hours, while its recovery to normal level takes place in several days. FDs are due to exclusion of GCRs because of their inability to diffuse ‘across’ the relatively strong and ordered IMF in the vicinity of interplanetary shock, in the sheath and/or flux–rope region of the CME. The FDs have also been the focus of many studies to examine a possible connection between the GCR flux and Earth’s climate via modulation of cloud cover (Lam & Rodger 2002; Laken et al. 2009). The FDs are routinely measured on the surface of Earth using neutron monitors and can be used to detect the arrival of CMEs and their speeds (Dumbović et al. 2018).

Keeping the Sun–Earth connection in mind, several studies have been undertaken in the last decades, before and after the launch of STEREO, to understand the propagation of CMEs and estimate their arrival times at Earth. The most recent reviews on ICMEs and their arrival times are by Kilpua et al. (2017), Vourlidas et al. (2019), Luhmann et al. (2020), Temmer (2021) and Zhang et al. (2021). Although much progress has been made in this direction, yet the accurate prediction of arrival times of CMEs remains difficult even today. In this review, we highlight several important earlier studies carried out to reach our present understanding of CMEs propagation. We also discuss open questions holding us back from progressing and the path forward for improving the accuracy in CME forecasting in the near future.

2. Studies on CME propagation before STEREO era

Although our review is focused on heliospheric propagation of CMEs, we would briefly mention a few of the studies on the origin of CMEs. There is a vast literature on the photospheric and coronal properties of source active regions that produce CMEs (Cliver & Hudson 2002; Kahler 2006; Georgoulis et al. 2019 and references therein). The initiation and early development of CMEs have been studied since the pioneering work on EUV waves by Dere et al. (1997) using the observations of the Extreme-ultraviolet Imaging Telescope (EIT) onboard SOHO. Recently, the availability of high resolution observations from Extreme UltraViolet Imager (EUVI) onboard STEREO and the Atmospheric Imaging Assembly (AIA) onboard SDO have further helped in exploring the solar surface signatures of CMEs (Vršnak & Cliver 2008; Liu & Ofman 2014 and references therein). Furthermore, the densities, temperatures, ionization states and Doppler velocities of CMEs have been studied using EUV spectral observations from the UltraViolet Coronagraph Spectrometer (UVCS), Coronal Diagnostic Spectrometer (CDS) and Solar Ultraviolet Measurements of Emitted Radiation (SUMER) instruments onboard SOHO and the Solar Optical Telescope (SOT) and the Extreme ultraviolet Imaging Spectrometer (EIS) instruments on Hinode (Raymond 2002; Kohl et al. 2006; Landi et al. 2010).

It is also noted that there have been a plethora of multi-wavelength studies on associating CMEs origins with their signatures on the Sun, such as streamers blowouts, solar flares, erupting prominences/filaments, coronal dimming, arcade formations and coronal waves (Tripathi et al. 2004; Burkepile et al. 2004; Benz 2008). These signatures of CMEs origin are primarily observed in wavelengths capable of imaging different layers of the solar atmosphere at varying temperatures and also plasma material of different ionization states. This is unlike the observations of CMEs by visible light coronagraphs and heliospheric imagers, which observe the angular dependent brightness of Thomson-scattered white-light from the free electrons in CMEs. Importantly, the white-light observations often sample the CMEs at heights different than the height, where the signatures of CMEs initiations are observed (Gopalswamy 2004; Webb et al. 2012). Therefore, it is difficult to make a direct association of CMEs and their associated phenomena at the solar surface. In the following, we will focus on the white-light and in-situ observations of CMEs.

The launch of twin STEREO spacecraft in 2006 and their subsequent observations of CMEs from the Sun to the Earth have revolutionized the understanding of propagation of CMEs. However, since the discovery and detection of CME in 1971 from a coronagraph onboard OSO-7 (Tousey 1973), thousands of CMEs have been observed from a series of space-based coronagraphs, e.g., Apollo Telescope Mount onboard Skylab (Gosling et al. 1974), Solwind coronagraph...
onboard P78-1 satellite (Sheeley et al. 1980), coronagraph/polarimeter onboard Solar Maximum Mission (SMM) (MacQueen et al. 1980), LASCO onboard SOHO (Brueckner et al. 1995). These observations were complemented by white light data from the ground-based Mauna Loa Solar Observatory (MLSO) K-coronameter, which had a FOV from 1.2–2.9 R⊙ (Fisher et al. 1981) and emission line observations from the coronagraphs at Sacramento Peak, New Mexico (Demastus et al. 1973) and Norikura, Japan (Hirayama & Nakagomi 1974).

Although the CMEs were formally discovered in 1971 (Tousey 1973) from a survey of literature, it is evident that consequences due to CMEs were noticed well before their discovery. For example, CMEs were observed at larger distances from the Sun in radio via interplanetary scintillation (IPS) observations from the 1960s. However, only around the 1980s, the association between IPS and CMEs could be established (Hewish et al. 1964; Houminer & Hewish 1972; Tappin et al. 1983). Attempts to observe the CMEs in regions in the inner heliosphere from 0.3 to 1.0 AU have also been made from the zodiacal light photometers on the twin Helios spacecraft during 1975–1983 (Richter et al. 1982). However, this attempt of observing the inner heliosphere was with the extremely limited FOV of zodiacal light photometers. Also, heliospheric imagers as Solar Mass Ejection Imager (SMEI) (Eyles et al. 2003) onboard the Coriolis spacecraft launched early in 2003, have observed several CMEs far from the Sun in the heliosphere.

The observations of CMEs in white-light images, kilometric radio observations from space, and metric radio IPS observations from the ground have resulted in several studies. In addition to this, in-situ observations of CMEs have also been made for decades (Klein & Burlaga 1982; Zurbuchen & Richardson 2006; Richardson & Cane 2010). The IPS techniques are based on the measurements of the fluctuating intensity level of several distant meter-wavelength radio sources. The observations of CMEs using IPS and the estimation of their parameters from several techniques have been described in earlier works (Hewish et al. 1964; Watanabe & Kakinuma 1984; Manoharan & Ananthakrishnan 1990; Bisi et al. 2008). In the present review, we will focus on the observations of CMEs in white-light imaging and in situ observations only.

Once a CME leaves the inner corona and starts moving into the interplanetary space filled with ambient solar wind medium, it takes the name of interplanetary CME (ICME), which undergoes different morphological and kinematic evolution throughout its propagation (Dryer 1994; Zhao & Webb 2003). ICMEs have been identified in in-situ observations and it was found that their plasma and magnetic field parameters are different from that of the ambient solar wind medium. Although it is possible to record a CME near the Sun and to identify the same in the in-situ observations, a one to one association between remote and in-situ observations of CMEs is not always easy to establish. There may be several factors responsible for this, which will be discussed in the following sections. It is understood that fast CMEs often generate large-scale density waves out into space, which finally steepens to form collisionless shock waves (Gopalswamy et al. 1998). This shock wave is similar to the bow shock formed in front of the Earth’s magnetosphere. Following the shock, there is a sheath structure, which has signatures of significant heating and compression of the ambient solar wind (Gopalswamy 2004; Manchester et al. 2005). After the shock and the sheath, the ICME structure is found. In the following sections, we describe the evolution of CMEs as observed from remote imaging and in-situ observations.

2.1 Observations of evolution of CMEs

The main problem in understanding the evolution of CMEs is our limited knowledge about their physical properties. In addition, remote white-light observations (e.g., coronagraphs and heliospheric imagers) allow tracking the propagation of CMEs, but these observations do not provide information on their magnetic field parameters. Associating the near Earth ICME observed in situ by the Advanced Composition Explorer (ACE) (Stone et al. 1998) and WIND (Ogilvie et al. 1995) spacecraft with Earth-directed front-side halo CMEs seen in LASCO coronagraph images, several attempts have been made in the past (Richardson & Cane 2004; Jian et al. 2006). Such studies have proved to be very difficult because of difficulties in determining the 3D speed of Earth-directed CMEs. Another problem is that an in situ spacecraft takes measurements along a certain trajectory through the ICME, therefore, it does not provide the global characteristics of CME plasma. SOHO/LASCO has detected well over 10^4 CMEs till date and still continues (http://cdaw.gsfc.nasa.gov/CME_list/) (Yashiro et al. 2004). SMEI also observed nearly 400 transients during its 8.5 year lifetime, and it was switched off in September 2011. In the following Sections 2.1.1 and 2.1.2, we describe the details of different sets of observations of CMEs.
2.1.1 Remote sensing observations of CMEs in white-light

In white-light images, CMEs are seen due to Thomson scattering of photospheric light from the free electrons of coronal and heliospheric plasma. The intensity of Thomson scattered light has an angular dependence, which must be considered for measuring the brightness of CMEs (Billings 1966; Vourlidas & Howard 2006; Howard & Tappin 2009). They are faint relative to the background corona, but much more transient, therefore, a suitable coronal background subtraction is applied to identify them. The advantage of white-light observations over radio, IR or UV observations is that Thomson scattering only depends on the observed electron density and is independent of the wavelength and temperature (Hundhausen 1993). Thomson scattering is a special case of the general theory of the scattering of electromagnetic waves by charged particles. Since the wavelength of white-light is smaller than the separation between the charge particles in the corona, and the energy of the white-light photons is lower than the rest mass energy of the particles in the corona, therefore, the solar photospheric light gets Thomson scattered by electrons in the corona and solar wind.

The details of Thomson scattering is given in earlier studies (Minnaert 1930; Billings 1966; Howard & Tappin 2009; Howard & DeForest 2012; Howard et al. 2013). These studies have shown that the received intensity of the scattered light by an observer depends on its location relative to the scattering source and incident beam (Figure 3). If scattered light is decomposed into two components, then for an observer, the intensity of the component seen as transverse to the incident beam is isotropic, while the intensity of the component seen as parallel to the projected direction of the incident beam (shown with red in Figure 3) varies as the square of cosine of scattering angle ($\chi$). The scattering angle is between the vector from scattering location to the observer which is along the line of sight and the vector from scattering source to the center of the Sun, which is along the incident beam. It means that $\chi$ is the Sun-scattering location-observer angle. Hence, the efficiency of Thomson scattering measured by an observer is minimum at $\chi = 90^\circ$, i.e., on Thomson surface (TS). TS is the surface of a sphere with diameter extending from Sun center to the observer, and all the points of closest approach to the Sun of each line of sight lies on the TS. However, TS is the point where incident light and electron density is found to be maximum. The combined effect of all the three factors is that the TS is the locus of points, where the scattering intensity is maximized for a fixed radial distance from the Sun. However, a spread of the observed intensity to larger distances from the TS is noted (Howard & DeForest 2012). This spreading is called ‘Thomson plateau’, which is greater at larger distances (elongations) from the Sun, where elongation ($\epsilon$) is the Sun-observer-scattering location angle. The details of TS and its theoretical background is discussed in Howard & Tappin (2009).

It has been shown that the sensitivity of unpolarized heliospheric imagers is not strongly affected by the geometry relative to the TS, and in fact, heliospheric imagers onboard STEREO have observed the CMEs very far from the TS (Howard & DeForest 2012). However, it has also been shown that the polarized brightness measurements of CMEs in the heliosphere, at larger distances from the Sun, are much more localized to the TS than the unpolarized brightness measurements (Howard et al. 2013). Conclusively, the observed brightness of a CME can change corresponding to its changing location across the TS and its distance from the Sun, and hence, corresponding to observers at different locations. This concept has implications for understanding how the kinematics and morphology of CMEs can appear to be different from observer’s perspectives.

2.1.2 In-situ observations of CMEs

Various plasma, magnetic field and compositional parameters of an ICME are measured by in-situ spacecraft at the instant when it intersects the ICME. The identification of ICME in in situ data is not very straightforward and it is based on several signatures, which are summarized below.

**Magnetic field signatures in the plasma** ICMEs are identified in in situ observations based on the increased...
magnetic field strength and reduced variability in the magnetic field (Klein & Burlaga 1982). A subset of ICMEs is known as Magnetic Clouds (MCs), which shows additional signatures, such as enhanced magnetic field greater than \( \approx 10 \) nT, smooth rotation of magnetic field vector by angles greater than \( \approx 30^\circ \) and plasma \( \beta \) (ratio of thermal and magnetic field energies) less than unity (Lepping et al. 1990).

**Dynamics signatures in the plasma** ICME can be identified *in-situ* by its characteristics of expansion during the propagation in the ambient solar wind. Due to expansion, CMEs also show depressed proton temperature in contrast to the ambient solar wind. ICME leading edge, i.e., front has speed greater than its trailing edge and the difference of speeds at boundaries is equal to two times the expansion speed of CME. Hence, a monotonic decrease in the plasma velocity inside an ICME is noticed (Klein & Burlaga 1982). It is also found that the normal solar wind is expected to show an empirical relation between proton temperature and solar wind speed (Lopez 1987) as given in Equations (1a) and (1b):
\[
T_{\text{exp}} = (0.031 V_{sw} - 5.1)^2 \times 10^3, \\
\text{when } V_{sw} < 500 \text{ km s}^{-1},
\]
\[
T_{\text{exp}} = (0.51 V_{sw} - 142) \times 10^3, \\
\text{when } V_{sw} > 500 \text{ km s}^{-1}.
\]

However, it is found that ICMEs do not show the same ‘expected’ proton temperature \( T_{\text{exp}} \) as it is for the ambient solar wind, which can be determined from Equations (1a) and (1b). In general, ICMEs typically have proton temperature \( T_p < 0.5 T_{\text{exp}} \) (Richardson & Cane 1995). It is also noted that in an ICME, the electron temperature \( T_e \) is greater than proton temperature \( T_p \). It is proposed that the ratio of electron to proton temperature, i.e., \( T_e / T_p > 2 \) is a good indicator of an ICME (Richardson et al. 1997).

**Compositional signatures in the plasma** The composition of an ICME is different than the ambient solar wind medium. *In-situ* observations have shown that alpha to proton ratio \( (\text{He}^{+2}/\text{H}) \) is higher \((>6\%)\) inside an ICME than its values in the normal solar wind. This suggested that an ICME also contains material from the solar atmosphere below the corona (Hirshberg et al. 1971; Zuruchen et al. 2003). It is observed that relative to the solar wind, an ICME shows an enhancement in the value of \( ^3\text{He}^{+2}/^4\text{He}^{+2} \), heavy-ion abundances (especially iron) and its enhanced charge states (Lepri et al. 2001; Lepri & Zurbuchen 2004). ICME associated plasma with enhanced charge states of iron suggests that CME source is ‘hot’ relative to the ambient solar wind. It is also noted that ICME shows relative enhancement of \( ^{1+}/^{O+6} \) (Richardson & Cane 2004; Rodriguez et al. 2004). However, few CMEs have been identified with unusual low ion charge states, such as the presence of singly-charged helium abundances well above solar wind values (Schwenn et al. 1980; Burlaga et al. 1998; Skoug et al. 1999). Such low-charge states suggest that the plasma may be associated with the cool and dense prominence material (Gopalswamy et al. 1998; Lepri & Zurbuchen 2010; Sharma & Srivastava 2012).

**Energetic particles signatures in the plasma** ICMEs have loop structures rooted at the Sun, therefore, the presence of bidirectional beams of suprathermal \((\geq 100 \text{ eV})\) electrons (BDEs) is considered as a typical ICME signature (Gosling et al. 1987). Sometimes such BDEs are absent when the ICME field lines in the legs of the loops reconnect with open interplanetary magnetic field lines. In addition, the short-term (few days duration) depressions in the galactic cosmic ray intensity and the onset of solar energetic particles are well associated with ICMEs (Zurbuchen & Richardson 2006).

**Association with shock and sheath** It is understood that some of the fast CMEs generate a forward shock ahead of them. Such shocks are wide and span several tens of degrees in heliospheric longitude, approximately two times the value of the angular width of the driver CME (Richardson & Cane 1993). In *in situ* observations, a forward shock is identified based on a simultaneous increase in the density, temperature, speed and magnetic field in the plasma. The shock is followed by a sheath region before the ICME/MC. These sheaths are identified as turbulent and compressed regions of solar wind having strong fluctuations in magnetic fields, which last for several hours (Zurbuchen & Richardson 2006). The magnetic fields in the compressed sheath region may be deflected out of the ecliptic, by draping around the ICME (McComas et al. 1989). The compressed and deflected magnetic field in the sheath results in geoeffectiveness. If the pre-shock magnetic field vector in the sheath region makes an angle of \(90^\circ\) with the normal to the shock surface, i.e., for perpendicular shock, then, the shock lead to stronger compression of the magnetic field in the sheath than that by parallel shocks. The strongly compressed sheath often give rise to more intense geomagnetic storms (Jurac et al. 2002).

Several studies have shown that different ICMEs show different signatures (Jian et al. 2006; Richardson...
& Cane 2010). For example, few ICMEs show signatures of flux ropes, while others do not. However, it is still not well understood why a few ICMEs are not observed as flux-rope in *in-situ* data. Similarly, cold filament material which is often observed in COR images as a ‘bright core’ following the cavity is rarely observed in *in situ* observations near 1 AU (Skoug et al. 1999; Lepri & Zurbuchen 2010).

It is important to mention here that no CMEs show all the signatures and therefore, there is no unique scheme to identify them in *in situ* observations. Also, different signatures may appear for different interval of time and hence, CMEs may have different boundaries in plasma, magnetic field and other signatures. This is possible as different signatures have their origin due to different physical processes. If we identify CMEs based on only a few signatures then, they may be falsely identified. Therefore, a practical approach is to identify as many signatures as possible. Such an approach helps for reliable identification of the CMEs in *in situ* observations, however, marking of their boundaries may still be ambiguous. Richardson & Cane (2010) have identified ~300 CMEs near the Earth during the complete solar cycle 23, i.e., between years 1996 and 2009. However, there are some other lists of CMEs observed near the Earth, which have compiled slightly differing number of ICMEs based on slightly different criteria (Richardson & Cane 1995; Cane & Richardson 2003; Richardson & Cane 2010).

Before the STEREO era, the biggest limitation of CME study was that most of the *in situ* data analysis was restricted to a single point observation at 1 AU, while ICMEs are large 3D structures. The limitation of a single point *in situ* observations is illustrated in Figure 4. The figure shows how a single point *in situ* instruments can measure different structures and hence, show different signatures of an ICME depending on the trajectory of the spacecraft through an ICME. Such a single point *in situ* spacecraft will also measure the different dynamics of an ICME based on its location within the ICME. Hence, in the absence of information about the part of ICME, which is being sampled by the *in situ* spacecraft, it would be difficult to find an association between the speed derived in COR FOV and the one measured *in situ*. Furthermore, since the CMEs evolve during their propagation from the Sun to the Earth, making an association between remote observations close to the Sun and *in situ* observations close to the Earth is erroneous. Therefore, multi-point *in situ* observations of an ICME from different viewing perspectives and investigation of the thermodynamic state of CMEs must be carried out.

2.2 Analysis methodology for CMEs kinematics

Several studies have been carried out to understand the CME kinematics using imaging observations from several space-based instruments (Schwenn 2006 and references therein). Among all the space-based instruments dedicated to observing CMEs, the SOHO/LASCO launched in 1995 can be considered as the most successful mission in observing thousands of CMEs, which led to hundreds of important research papers. SOHO/LASCO consists of three nested coronagraphs C1 (no longer operating since June 1998), C2 and C3 that have observed the solar corona from 1.1 to 30 $R_\odot$ with overlapping FOVs. Using these observations, several studies were carried out to estimate the source location, mass, kinematics, morphology and arrival times of CMEs (Cyr et al. 2000; Xie et al. 2004; Schwenn et al. 2005). Also, to explain the initiation and propagation of CMEs, several theoretical models have been developed (Chen 2011 and references therein). These models differ from one another considerably in the involved mechanism of the progenitor, triggering and the eruption of a CME. Based on the angular width of a CME observed in coronagraphic images, CMEs were classified as halo, symmetric halo, asymmetric halo, partial halo, limb and narrow CMEs. Furthermore, based on the acceleration profile of a CME, the CMEs were classified as gradual and impulsive CMEs (Sheeley et al. 1999; Srivastava et al. 1999). Despite the observations of CMEs with extremely low and high
Figure 5. The three different phases of kinematics of a CME and its association with temporal evolution of GOES, soft X-ray flux is shown. The initiation, acceleration and propagation phase of the CME kinematics correspond to the preflare, rise and decay phase of the associated flare, respectively (reproduced from Zhang & Dere 2006).

speeds, it is believed that all CMEs belong to a dynamical continuum having no difference in the physics of their initiation process (Crooker 2002). With the availability of complementary disk observations of solar active regions and prominences, statistical studies on the association of different types of CMEs with flares and prominences have also been carried out in detail (Kahler 1992; Gopalswamy et al. 2003b).

It is found that a typical CME shows a three-phase kinematic profile: first, a slow rise over tens of minutes, then a rapid acceleration between $1.4 R_\odot$ and $4.5 R_\odot$ during the main phase of a flare, and finally a propagation phase with constant or decreasing speed (Zhang & Dere 2006). These three distinct phases of a CME are shown in Figure 5. It is noted that after a rapid acceleration phase, the CME accelerates or decelerates slowly in the FOV of coronagraphs (Cyr et al. 2000; Yashiro et al. 2004). The estimated total mass of CMEs range from $10^{10}$ to $10^{13}$ kg, and the total energy from $10^{20}$ to $10^{26}$ J. The average mass and energy of a CME is $1.4 \times 10^{12}$ kg and $2.6 \times 10^{23}$ J, respectively (Vourlidas et al. 2002).

The source locations of the majority of CMEs are within 25$^\circ$ from the solar equator, around the solar minimum, although few CMEs are seen at higher latitudes also (Cyr et al. 2000). Excluding the partial and full halo CMEs, the apparent angular width of CMEs is found to vary from few degrees to >120$^\circ$ with an average value of about $\approx 50^\circ$ (Yashiro et al. 2004). These properties derived from a statistical study will also depend on the sensitivity of the coronagraphs and the selection of the sample of CMEs. It is noted that in the pre-STEREO era, the angular width, speed and mass of CMEs were often estimated from the 2D coronagraphic images of CMEs. Such estimates are subject to the projection and perspective effects. These studies were based on the plane of sky assumption, i.e., CMEs are propagating perpendicular to the Sun-observer line. Therefore, if this assumption of the plane of sky fails, the speed, mass and energies of CMEs will be underestimated (Vourlidas et al. 2010), while the angular width will be severely overestimated (Burkepile et al. 2004).

2.3 Arrival time of CMEs at the Earth

Realizing the consequences of CMEs on our modern high-tech society, several studies were dedicated at finding a correlation between the intensity of magnetic disturbances on the Earth and the characteristics of CMEs estimated near the Sun (Gosling et al. 1990; Srivastava & Venkatakrishnan 2002, 2004). In the context of space weather, understanding the heliospheric evolution of CMEs and predicting their arrival times at the Earth is a major objective of various forecast centers. The prediction of CME/shock arrival time means that forecasters utilize the observables of solar disturbance obtained prior to arrival as inputs to predict whether/when they will arrive. Longer lead time in prediction is yielded if the solar observables are used. The arrival time of CMEs at 1 AU can be related to their characteristics (velocity and acceleration) near the Sun to develop the prediction methods for CME’s arrival time. Different kinds of models of CME/shock arrival time prediction have been developed, e.g., empirical models, expansion speed model, drag-based models, physics-based models and MHD models.

Several studies of evolution of CMEs have been carried out using SOHO/LASCO observations, in-situ observations near the Earth by ACE and WIND combined with modeling efforts (Andrews et al. 1999; Wood et al. 1999; Gopalswamy et al. 2000a, 2001b, 2005; Yashiro et al. 2004). These studies were based on the understanding of the kinematics of CMEs using two-point measurements, one near the Sun up to a distance of $30 R_\odot$ using coronagraph (LASCO/C2 and C3) images, and the other near the Earth using in situ instruments. Using the LASCO images, one could estimate the projected speeds of CMEs, although we lacked information about the 3D speed and direction of the Earth-directed CMEs. These studies were carried out to calculate the kinematics and the travel time of CMEs from the Sun to the Earth, suffered from a lot of assumptions regarding
the geometry and evolution of a CME in the interplanetary medium (Howard & Tappin 2009; Vršnak et al. 2010).

Several models, based on the empirical relationship between measured projected speeds of CMEs and their observed arrival time at 1 AU, have been developed to forecast the CME arrival time at a particular heliocentric distance (Gopalswamy et al. 2001a; Vršnak & Gopalswamy 2002; Schwenn et al. 2005). Vandas et al. (1996) found that the transit time (in h) to 1 AU for the CME flux rope (cloud/driver) leading edge is \( T_{\text{driver}} = 85 - 0.014V_i \) for a slow background solar wind speed (say 361 km s\(^{-1}\)), and \( T_{\text{driver}} = 42 - 0.0041V_i \) for a faster background solar wind speed (say 794 km s\(^{-1}\)). Here \( V_i \) (km s\(^{-1}\)) is the propagation speed of the leading edge of CME at 18 \( R_\odot \). Then, the transit time of the shock preceding the magnetic cloud is \( T_{\text{shock}} = 74 - 0.015V_i \) for slow solar wind and \( T_{\text{shock}} = 43 - 0.006V_i \) for fast solar wind. It is found that the difference in time between the CME launch on the Sun and the time when the associated geomagnetic storm reaches its peak is about 80 h (Brueckner et al. 1998).

Among the most typical and widely used prediction models are empirical CME arrival (ECA) and empirical shock arrival (ESA) models. ECA model consider that a CME has an average acceleration up to a distance of 0.7–0.95 AU (Gopalswamy et al. 2001a). After the cessation of acceleration, a CME is assumed to move with a constant speed. They found that the average acceleration has a linear relationship with the initial plane-of-sky speed of the CME. The ECA model has been able to predict the arrival time of CMEs within an error of ±35 h with an average error of 11 h. Later, an ESA model was able to predict the arrival time of CMEs within an error of approximately ±30 h with an average error of 12 h (Gopalswamy et al. 2005). The ESA model is a modified version of the ECA model in which a CME is considered to be the driver of magnetohydrodynamic (MHD) shocks. The other assumption is that fast mode MHD shocks are similar to gas dynamic shocks. The gas dynamic piston–shock relationship is thus utilized in this model. Various efforts have been made to derive an empirical formula for CME arrival time, based on the projected speed of a large number of CMEs (Wang et al. 2002; Zhang et al. 2003; Srivastava & Venkatakrishnan 2004; Manchester et al. 2004).

The empirical models adopt relatively simple equations to fit the relations between the arrival time of the CME disturbance at the Earth and their observables, such as initial velocity near the Sun. In the majority of these empirical models, the initial speeds of CMEs were measured from plane of sky LASCO/SOHO observations and therefore, the measured kinematics are not representative of the true CME motion. To overcome plane-of-sky effects, a study of 57 limb CMEs was made to derive an empirical relationship between their radial and expansion speeds as \( V_{\text{rad}} = 0.88V_{\text{exp}} \) (Dal Lago et al. 2003). This result led to the use of lateral expansion speed as a proxy for the radial speed of halo CMEs that could not be measured. Also, in another study of 75 events, an empirical formula for transit time of CMEs to Earth was derived as \( T_{\text{tr}} = 203 - 20.77\ln(V_{\text{exp}}) \) (Schwenn et al. 2005). Their results show that the formula can be used for predicting ICME arrivals with a 95% error margin of about 24 h. Such empirical models have inherent difficulties as they are only math-fit of the measured CME speed and arrival time, but do not consider the physics of CME evolution through the ambient solar wind.

Furthermore, a few attempts have been made to fit the observed kinematics profiles of CMEs using an appropriate mathematical function (Gallagher et al. 2003). These studies, using SOHO/LASCO observations, are subject to large uncertainties due to projection effects. To overcome the projection effects, method such as forward modeling, which approximates a CME as a cone (Zhao et al. 2002; Xie et al. 2004; Xue et al. 2005) and varies the model parameters to best fit the 2D observations, have been used to estimate the CME kinematics. However, this derived kinematics is also subject to several new sources of errors due to the presumed geometry of the CME. Another method known as polarimetric technique, using the ratio of unpolarized to polarized brightness of the Thomson-scattered K-corona, has been applied to estimate the average line of sight distance of CME from the instrument plane of the sky (Moran & Davila 2004). However, the technique of polarization ratio is only applicable up to \( \approx 5 R_\odot \) because beyond this, the F-corona cannot be considered as unpolarized. Thus, the estimation of 3D kinematics of a CME beyond a few solar radii from the Sun, was largely undetermined in the pre-STEREO era.

Many studies have also shown that CMEs interact significantly with the ambient solar wind as they propagate in the interplanetary medium, resulting in acceleration of slow CMEs and deceleration of fast CMEs towards the ambient solar wind speed (Lindsay et al. 1999; Gopalswamy et al. 2000a, 2001a; Yashiro et al. 2004; Manoharan 2006; Vršnak & Žic 2007). It was shown that CME transit time depends on both the CME take-off speed and the background solar wind speed. The interaction between the solar wind and the CME is
understood in terms of a ‘drag force’ (Cargill et al. 1996; 
Vršnak & Gopalswamy 2002). Therefore, the analytical 
models developed are based on the equation of motion 
of CMEs, where the drag acceleration/deceleration has 
a quadratic dependence on the relative speed between 
CME and the background solar wind. It was found that 
the measured deceleration rates are proportional to the 
relative speed between CME and the background solar 
wind, as well as a dimensionless drag coefficient (cd) 
(Vršnak 2001; Vršnak & Gopalswamy 2002; Cargill 
2004). Recently, a discussion on the variation of the 
drag coefficient (cd) with heliocentric distance was 
made (Subramanian et al. 2012). They adopt a micro-
physical prescription for viscosity in the turbulent solar 
wind to obtain an analytical model for the drag coeffi-
cient. Furthermore, a simple yet powerful drag-based 
model (DBM) is developed, which can estimate the 
Sun–Earth transit time of CMEs and their impact speed 
at 1 AU (Vršnak et al. 2013). The DBM has also been 
used widely in the STEREO era in several studies as 
described in Section 3.

The observations have revealed that the dynamics of 
CMEs are governed mainly by drag force beyond a cer-
tain distance from the Sun. This is perhaps the reason 
why a few analytical DBMs (Vršnak & Žic 2007; Lara 
& Borgazzi 2009; Vršnak et al. 2010) have been used 
widely in the literature. However, some earlier studies 
acknowledge the role of Lorentz force even during the 
propagation phase of a CME (Kumar & Rust 1996; Sub-
ramanian & Vourlidas 2005, 2007; Subramanian et al. 
2014). In the direction of modeling efforts, a few numeri-
cal MHD simulation models (Odstrcil et al. 2004; 
Manoharan et al. 2004; Smith et al. 2009) have been 
developed and used to predict CME arrival times (Dryer 
et al. 2004; Feng et al. 2009; Smith et al. 2009). Despite 
several studies on CME propagation using observations 
combined with models, very little is known about the 
extact nature of the forces governing the propagation 
of CME.

A physics-based MHD numerical model is the 
coupled Wang–Sheeley–Arge (WSA) + ENLIL + cone 
model (Odstrcil et al. 2004), which has often been used 
to simulate the propagation and evolution of CMEs in 
interplanetary space and provides a 1–2 day lead time 
forecasting for major CMEs (Taktakishvili et al. 2009; 
Pizzo et al. 2011). WSA is a quasi-steady global solar 
wind model that uses synoptic magnetograms as inputs 
to predict ambient solar wind speed and interplaneto-
tary magnetic field polarity at Earth (Wang & Sheeley 
1995; Arge & Pizzo 2000). The ENLIL model is a time-
dependent, 3D ideal MHD model of the solar wind in 
the heliosphere (Odstrcil et al. 2002, 2004). The cone 
model assumes a CME as a cone with constant angular 
width in the heliosphere (Zhao et al. 2002; Xie et al. 
2004). The input of ENLIL at its inner boundary of 21.5 
R⊙ is taken from the output of WSA to get the back-
ground solar wind flows and interplanetary magnetic 
field.

A physics-based prediction model named ‘Shock 
Time of Arrival’ (STOA) model has been developed 
based on the theory of blast waves from point explo-
sions. This concept was revised by introducing the 
piston-driven concept (Dryer 1974; Smart & Shea 
1985). Another such model is the ‘Interplanetary Shock 
Propagation Model’ (ISPM), which is based on a 
2.5D MHD parametric study of numerically simulated 
shocks. The model demonstrates that the organizing 
parameter for the shock is the net energy released into 
the solar wind (Smith & Dryer 1990). The ‘Hakamada– 
Akasofu–Fry version 2’ (HAFv.2) model is a ‘modified 
kinematic’ solar wind model that calculates the solar 
wind speed, density, magnetic field and dynamic pres-
sure as a function of time and location (Dryer et al. 
2001, 2004; Fry et al. 2001, 2007; Smith et al. 2009). 
This model gives a global description of the propaga-
tion of multiple and interacting shocks in non-uniform, 
stream–stream interacting flows of solar wind in the 
ecliptic plane. The STOA, ISPM and HAFv.2 models 
use similar input solar parameters (i.e., source location 
of the associated flare, start time of the metric type 
II radio burst, proxy piston driving time duration and 
background solar wind speed).

We note that some of the aforementioned models 
are complicated, while others are rather simple and 
easy, however, no significant differences are found 
between their prediction capabilities of CME arrival 
time. The predictions yield a root-mean-square error of 
≈12 h and a mean absolute error of ≈ 10 h for a 
large number of CMEs. Many factors are responsi-
bile for the limited accuracies of these models, e.g., (1) 
The input parameters (kinematics and morphology) of 
the model have their own uncertainties. (2) The real-
time background solar wind condition into which CME 
travels is difficult to either observe or simulate from 
MHD. (3) The change in the kinematics of the CME 
due to its interaction with other large or small scale 
solar wind structures. These factors are difficult to 
be taken into account in a single model. Improvement 
in the accuracy of these arrival time models, requires 
a better understanding of both the heliospheric evo-
lution of CME and the ambient solar wind medium. 
Using the observations of CMEs from instruments 
onboard STEREO, the heliospheric evolution can be 
better understood by imposing some constraints on the
models and methods developed based on the observations from SOHO/LASCO.

3. Studies on CME propagation in STEREO era

The twin STEREO (Kaiser et al. 2008) spacecraft, launched late in 2006, can observe CMEs in the heliosphere using its identical optical, in situ particles, fields and radio instruments on each spacecraft. These instruments are in four different measurement packages named as Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) (Howard et al. 2008), In situ Measurements of PArticles and CME Transients (IMPACT) (Luhmann et al. 2008), PLAsma and SupraThermal Ion Composition (PLASTIC) (Galvin et al. 2008) and S/WAVES. The IMPACT and PLASTIC packages can provide a chance to measure the in situ signatures of CMEs at 1 AU from two vantage points. The suite of instruments in SECCHI package consists of two white-light coronagraphs (COR1 and COR2), an Extreme Ultra-violet Imager (EUVI) and two white-light heliospheric imagers (HI1 and HI2). The SECCHI package have the capability to continuously image a CME from its lift-off in the corona out to 1 AU and beyond.

The twin STEREO spacecraft move ahead and behind the Earth in its orbit with their angular separation increasing by 45° per year. The STEREO mission overcomes a large observational gap between near Sun remote observations and near-Earth in situ observations and provides information on the 3D kinematics of CMEs due to multiple viewpoints on the solar corona. Thus, in the STEREO era, the three-dimensional 3D aspects of CMEs could be studied for the first time. Such 3D studies on CMEs was not done in pre-STEREO era when coronagraphic observations were available only from one location along the Sun–Earth line, as discussed in Section 2. Such unique observations led to the development of various 3D reconstruction techniques, e.g., tie-pointing method (Inhester 2006), forward modeling (Thernisien et al. 2009), etc. Also, several other techniques were developed that are derivatives of the tie-pointing technique: the 3D height-time technique (Mierla et al. 2008), local correlation tracking and triangulation (Mierla et al. 2009), and triangulation of the center of mass (Boursier et al. 2009). These methods have been devised to obtain the 3D heliographic coordinates of CME features in the SECCHI/CORs FOV.

The kinematics of CMEs in 3D over a range of heliocentric distances and their heliospheric interaction have been investigated by exploiting STEREO/HI observations (Davis et al. 2009; Mierla et al. 2010; Temmer et al. 2011; Harrison et al. 2012; Liu et al. 2012; Lugaz et al. 2012; Mishra & Srivastava 2013, 2014; Mishra et al. 2015b). In an effort to combine observations and model, Byrne et al. (2010) applied the elliptical tie-pointing technique on the COR and HI observations and determined the angular width and deflection of a CME of 12 December 2008. They used the derived kinematics as inputs in the ENLIL model (Odstrčil & Pizzo 1999) to predict the arrival time of a CME at the L1 near the Earth.

It is noted that the 3D kinematics of CMEs may change beyond the CORs FOV either due to drag forces acting on them or due to CME–CME interaction in the heliosphere. Also, a CME may be deflected by another CME and by nearby coronal holes during its propagation in the heliosphere (Gopalswamy et al. 2009). To demonstrate the drag forces acting on the CMEs, Maloney & Gallagher (2010) estimated 3D kinematics of CMEs in the inner heliosphere exploiting STEREO observations and pointed out different forms of drag force for fast and slow CMEs. The aerodynamic drag force acting on different CMEs will be different and its magnitude will change as the CME propagate in the heliosphere. Therefore, the estimation of the CME arrival time using only the 3D speed estimated from the 3D reconstruction method in COR FOV may not be accurate (Kilpua et al. 2012).

In the STEREO era, in addition to SECCHI imaging suite, each of the STEREO carries its IMPACT and PLASTIC suite, which can make the in situ observations of the ICMEs. The in situ observations of ICMEs from ACE and WIND spacecrafts located along the Sun–Earth line, as well as from STEREO located off-Sun–Earth line have been made for several cases (Rodriguez et al. 2011; Möstl et al. 2014). Exploiting the in situ observations of CME by twin STEREO, Kilpua et al. (2009) suggested that high latitude CMEs can be guided by the polar coronal fields and they can be observed as ICME close to the ecliptic plane. In another study, Kilpua et al. (2011) emphasized that an ICME cannot be explained in terms of simple flux ropes models because they are observed as different in situ structures at both the STEREO spacecraft even when the separation between the spacecraft were only few degrees in longitude. Despite the advantage of multi-point in situ observations, it is still unclear whether all CMEs have flux ropes or in other words, whether all interplanetary CMEs are magnetic clouds. Also, it is not well understood how a remotely observed CME evolves into an ICME observed in situ in the solar wind.
Two recently launched space missions, Parker Solar Probe (PSP) in August 2018 (Fox et al. 2016) and Solar Orbiter (SO) in February 2020 (Müller et al. 2020), are devoted to revolutionizing our understanding of the solar activity, corona, solar wind, generation, acceleration and transport of solar energetic particles (SEPs). Both PSP and SO carry a comprehensive suite of in-situ and remote-sensing instrumentation. These spacecraft intend to reach much closer to the Sun and perform detailed in situ measurements of nascent solar wind. PSP having varying elliptical orbits around the Sun in the ecliptic plane will approach within 10 \( R_\odot \) from the center of the Sun by 2025. SO having highly elliptical and inclined orbits around the Sun will approach within 0.28 AU from the center of the Sun by 2025. SO having increasing orbital tilt will reach 18° in the nominal mission (first in March 2025), 25° at the start of the extended mission (first in January 2027), and 33° in the extended mission (first in July 2029). The Solar Orbiter Heliospheric Imager (SoloHI) (Horbury et al. 2020), Metis coronagraph (Antonucci et al. 2020) and the Wide-field Imager for Solar Probe (WISPR) (Vourlidas et al. 2016) onboard PSP will gather images of both quasi-steady flow and transient disturbances in the solar wind over a large FOV. The differing orbits of the two spacecraft provide two potentials of sight through the corona and accelerating solar wind, which is further aided by SOHO/LASCO along the Sun–Earth line and by STEREO-A. There have been several studies exploiting the remote observations of CMEs by PSP and SO (Hess et al. 2020; Rouillard et al. 2020; Laker et al. 2021). Also, many studies have been reported utilizing the in-situ observations of solar wind by PSP and SO (McComas et al. 2019; Horbury et al. 2020; Lawrance et al. 2020). These two missions promise to revolutionize our understanding of the Sun–heliosphere system, but the results from these missions are not included in the present review. Instead, we focus on the heritage of the recent STEREO era, providing unprecedented imaging observations from multiple viewpoints that have led to the development of several algorithms and software tools in the last 15 years. The following section focuses on the importance of deriving 3D morphology, kinematics and arrival times of large-scale solar wind structures.

3.1 Remote observations of CMEs in the heliosphere

In the following, we will focus the white-light imaging observations from only CORs and HIs onboard STEREO.

3.1.1 SECCHI/COR observations As mentioned earlier, SECCHI has two white-light coronagraphs, COR1 is a Lyot internally occulting refractive coronagraph (Lyot 1939) and its FOV is from 1.4 to 4.0 \( R_\odot \). The internal occultation enables better spatial resolution closer to the limb. COR1 has a resolution of 7.5'' per pixel with a cadence of 8 min. Another coronagraph, COR2 is an externally occulted Lyot coronagraph similar to LASCO-C2 and C3 coronagraphs onboard SOHO spacecraft with FOV from 2.5 to 15 \( R_\odot \). COR2 observes with a cadence of 15 min and with a resolution of 14.7'' per pixel. The brightness sensitivity of COR1 and COR2 is \( \approx 10^{-10} \) and \( 10^{-12} \ B_\odot \), respectively. The calibration, operation, mechanical and thermal design of COR1 and COR2 coronagraphs are described in Howard et al. (2008).

3.1.2 SECCHI/HI observations SECCHI/Heliospheric Imagers (HIs) detect photospheric light scattered from free electrons in K-corona and interplanetary dust around the Sun (F-corona) similar to CORs. HI also detects the light from the stars and planets within its FOV. The F-corona is stable on a timescale far longer than the nominal image cadence of 40 and 120 min for the HI1 and HI2 cameras, respectively. The HI1 and HI2 telescopes have an angular FOV of 20° and 70° and are directed at solar elongation angles of about 14° and \( \approx 54° \) in the ecliptic plane. The HI-A telescopes are pointed at elongation angles to the east of the Sun, whilst HI-B axes are pointed to the west. HI1 and HI2 observe the heliosphere from 4° to 24° and 18.7° to 88.7° solar elongation, respectively (Eyles et al. 2009). Hence, HI1 and HI2 have an overlap of about 5° in their FOVs and therefore, permit photometric cross-calibration of the instruments. The HI1 and HI2 are with a resolution of 70'' per pixel and 4' per pixel, respectively. The brightness sensitivity of HI1 and HI2 is \( 3 \times 10^{-15} \) and \( 3 \times 10^{-16} \ B_\odot \), respectively (Eyles et al. 2009). The images of CMEs observed in the FoV of COR2, HI1, and HI2 are shown in Figure 6. The number of CME ‘events’ reported using the HIs onboard STEREO is now more than 1000 (http://www.stereo.rl.ac.uk/HIEventList.html), although <100 have been discussed so far in the scientific literature (Harrison et al. 2018).

It must be emphasized that HI-A and HI-B view from two widely separated spacecraft at similar planetary angles (Earth–Sun–spacecraft), thus providing a stereographic view. Figure 7(a) shows the overall FOVs of HI instruments projected onto the ecliptic plane. The two lines of sight drawn with arrows from both STEREO-A (red) and STEREO-B (blue) spacecraft represent the
inner and outer edges of FOVs of HI. The region of the heliosphere observed in the common FOV of HI-A and HI-B only will have a stereoscopic view from STEREO. It is also clear from this figure that a CME directed towards the Earth can be observed continuously from the Sun to the Earth and beyond from both HI-A and HI-B telescopes. In this scenario, a CME directed eastward from the Earth and STEREO-B can only be observed in HI-A FOV, but not in HI-B FOV. Similarly, a CME directed westward from the Earth and STEREO-B will be observed only in HI-B FOV, but not in HI-A FOV.

From Figure 7, it can be noted that as the separation (summation of longitude of both STEREO) between the STEREO-A and STEREO-B increases with time, the region of the heliosphere observed simultaneously by both HI-A and HI-B also changes. From Figure 7(b), it is clear that separation between STEREO-A and B was $\sim 175^\circ$ around December 2010, any Earth-directed CMEs during that time cannot be observed near the Sun. They can be observed only a little far from the Sun by both HI-A and HI-B. Therefore, the continuous (Sun to Earth) tracking of CMEs during that time cannot be observed near the Sun. From Figure 7(c), it is clear that the STEREO spacecraft are behind the Sun from the Earth’s perspective, i.e., the separation between them is $> 180^\circ$, HI-A and HI-B will not provide continuous coverage between the Sun and the Earth along the ecliptic. Hence, in this scenario also, an Earth-directed CME will not be observed for a significant distance close to the Sun. The other issue of ‘detectability’ of a CME arises when the STEREO spacecraft are behind the Sun. In this case, if the CME is directed towards the Earth, then it is substantially far-sided for both the STEREO spacecraft. Hence, the distance between the CME and STEREO increases with time and also as the CME diffuses with time, therefore, its detection is difficult, but not impossible. Even in such a scenario, some of the Earth-directed CMEs have been detected well in HI FOV (Liu et al. 2013). In Figure 7(d), the STEREO spacecraft are on the other
side of the Sun with respect to the Earth. In this scenario, the Earth does not appear in HI FOV, which implies that any CME propagating towards the Earth will not be observed during its journey from the Sun to the Earth. We highlighted that the communication with STEREO-B got lost around October 2014 and was re-established for a short duration only in August 2016. It has been out of contact since September 2016; therefore, at present, only STEREO-A is operating in the absence of STEREO-B. Such a loss of STEREO-B has limited the operational potential of the overall STEREO mission.

### 3.2 Analysis and methodology for CMEs kinematics using COR2 observations

Various 3D reconstruction methods have been developed, which can be used on SECCHI/COR observations, i.e., for a CME feature close to the Sun. These have been reviewed in Mierla et al. (2010). The most widely used 3D reconstruction techniques on the SECCHI/COR observations of CMEs are the tie-pointing method (Inhester 2006; Thompson 2009) and forward modeling method (Thernisien et al. 2009). These methods are often used to estimate the kinematics of CMEs close to the Sun, i.e., before they enter into the HI FOV.

#### 3.2.1 TP reconstruction

The tie-pointing (TP) method of stereoscopic reconstruction is based on the concept of epipolar geometry. The position of two STEREO spacecraft and the point to be triangulated define a plane called epipolar plane (Inhester 2006). Since every epipolar plane is seen head-on from both STEREO spacecraft, it is reduced to a line in the respective image projection. This line is called epipolar line. Epipolar lines in each image can easily be determined from the observer’s position and the direction of observer’s optical axes. Any object which lies on a certain epipolar line in one image must lie on the same epipolar line in the other image. This straight forward geometrical consequence is known as epipolar constraint.

Due to the epipolar constraint, finding the correspondence of an object in the contemporaneous images from both spacecraft, reduces in finding out correspondence along the same epipolar lines in both images. Once the correspondence between the pixels is found, the 3D reconstruction is achieved by calculating the line of sight rays corresponding to those pixels and on back tracking them in 3D space. Since the rays are constrained to lie in the same epipolar plane, they intersect at a point on tracking backwards. This procedure is called TP. The point of intersection of both lines of sight gives the 3D coordinates of the identified object or feature in both sets of images. Before implementing the method, the processing of SECCHI/COR2 images and the creation of minimum intensity images and then, its subtraction from the sequence of processed COR2 images are carried out as described in earlier studies (Mierla et al. 2008; Srivastava et al. 2009). This method has a graphical user interface (GUI) in the interactive data language (IDL) software and has been widely used in several studies to estimate the 3D coordinates of a CME’s feature (Mishra & Srivastava 2013; Mishra et al. 2014).

#### 3.2.2 Forward modeling method

In the forward modeling method, a specific parametric shape of CME is assumed and iteratively fits until it matches with its actual image. Thernisien et al. (2009) developed a method assuming a Graduated Cylindrical Shell (GCS) model to match the CME observed by SECCHI/COR2-A and B. The GCS model represents the flux rope structure of CMEs with two shapes; the conical legs and the curved (tubular) fronts (Figure 8). The resulting shape is like a ‘hollow croissant’. The model also assumes that the GCS structure moves in a self-similar way. In principle, this technique can also be applied to HI images, however, the technique is widely applied to COR2 images. This is because, in COR2 FOV, the flux rope structure of CMEs is well identified, while it is not fully developed in COR1 FOV and is too faint in the HI FOV.

GCS model fitting tool in IDL involves simultaneous adjusting six model parameters so that the resulting GCS flux structure matches well with the observed flux rope structure of the CME (Thernisien 2011). These six parameters, including the longitude, latitude, tilt angle of the flux ropes with the height of the legs, half-angle between the legs and aspect ratio of the curved front are adjusted to match the spatial extent of the CME. These have been discussed in detail in Thernisien et al. (2009). The best-fit six parameters obtained are used to calculate various geometrical dimensions of a CME.

From a space weather perspective, the main advantage of using SECCHI/COR data and the 3D reconstruction methods described above is that it enables estimation of true speed and hence, forecasting of the arrival time of CMEs near the Earth with better accuracy. However, information on the deceleration, acceleration or deflection experienced by a CME beyond COR2 FOV cannot be obtained. This may lead to an erroneous arrival time estimation.
3.3 Reconstruction methods using COR and HI observations

It is often observed that when CMEs leave the coronagraphic FOV, the Thomson scattered signal becomes too low to identify a particular feature in both sets of images obtained by STEREO-A and STEREO-B. Therefore, a method of time-elongation map (J-map), initially developed by Sheeley et al. (1999) for SOHO/LASCO images, is used to track a CME feature in the interplanetary medium. This technique has been implemented on STEREO/HI images to reveal the outward motion of plasma blobs in the interplanetary medium (Rouillard et al. 2009). In the STEREO era, the J-maps are now considered necessary for the best exploitation of HI observations to track a CME far away from the Sun (Davis et al. 2009; Harrison et al. 2012). The details on J-maps and its utility to derive the kinematics of CMEs are described in Sections 3.3.1–3.3.4.

3.3.1 Construction of J-maps

For tracking CMEs in the heliosphere, J-maps, also known as time-elongation maps, have often been constructed using long-term background-subtracted running difference images taken from COR2, HI1 and HI2 on STEREO-A and STEREO-B spacecraft (Davis et al. 2009; Robbrecht et al. 2009; Möstl et al. 2011; Mishra et al. 2014). The running difference reveals the changes in electron density between consecutive images. Before computing running differences, the HI image pair is aligned to prevent the stellar contribution in the difference images. This alignment requires precise pointing information of the HI instruments (Davis et al. 2009). For this purpose, it is better to use the level 2 HI data that were corrected for cosmic rays, shutterless readout, saturation effects, flat fields and instrument offsets from spacecraft pointing. A long-term background image is also subtracted to prepare level 2 HI data.

To construct J-maps, Mishra et al. (2014) first calculated the elongation and position angles for each pixel of the difference images from COR and HI and extracted a strip of constant position angle along the position angle of the Earth. They considered the position angle tolerance for the COR2 images as 5° and 2.5° for both HI1 and HI2. Thereafter, they binned the pixels of the extracted strip over a specific elongation angle bin size, viz., 0.01° for COR2 and 0.075° for both HI1 and HI2. They also took the resistant mean of all pixels over a position angle tolerance in each bin to represent the intensity at a corresponding elongation angle. The resistant mean stacked as a function of time and elongation will produce a time-elongation map (J-map). Following this procedure, a typical J-map is shown in Figure 9 in which the bright curves with positive inclination, reveal the propagation of a CME feature.

Using J-map, one can track CME features in the heliosphere and derive the elongation-time profile. There have been the development of a plethora of 3D reconstruction techniques, which use the time-elongation profile of a CME to estimate its heliospheric kinematics. These reconstruction techniques are based on different assumptions, which make them independent of each other to some degree, as described below.
at greater distances from the Sun, several attempts have been made to estimate the 3D kinematics of CMEs using single viewpoint observations from HIs. Such single spacecraft reconstruction methods are described below.

**Point-P method**
Point-P (PP) method was developed by Howard et al. (2006) to convert the elongation angle to distance from the Sun center. This method was developed soon after the launch of SMEI (Eyles et al. 2003), and can measure the elongation angle of a moving feature of a CME. The accuracy of this conversion is constrained by the effects of the Thomson scattering process and the geometry of CMEs, which govern their projection in the images. In this method, to remove the plane of sky approximation especially for HIs, it is assumed that a CME is a wide circular structure centered on the Sun and an observer looks and tracks the point, where the CME intersects the Thomson surface (Vourlidas & Howard 2006). Under these assumptions, radial distance \( R_{PP} \) of CME from the Sun center is derived, \( R_{PP} = d_0 \sin \epsilon \), where \( \epsilon \) is the measured elongation of a moving feature and \( d_0 \) is the distance of the observer from the Sun. This method has been used in several earlier studies (Howard et al. 2007; Wood et al. 2009, 2010; Mishra et al. 2014). In the case where small (elongation) angle approximation can be applied, the PP method is close to the plane of sky approximation.

However, the concept of Thomson surface has been de-emphasized by showing that the maximum intensity of scattered light per unit density is spread over a broad range of scattering angles, which is called Thomson plateau (Howard & DeForest 2012; Howard et al. 2013). They concluded that CME features can be observed far from the Thomson surface and that their detectability is governed by the location of the feature relative to the plateau rather than the Thomson surface. The existence of this Thomson plateau and the oversimplified CME geometry assumed in the PP method are likely to lead to significant errors in the estimated kinematics of CMEs.

**Fixed-phi (FP) method**
Analyzing LASCO data, Sheeley et al. (1999) introduced the concept that the time-elongation map shows an apparent acceleration and deceleration of a CME due to imposed projective geometry on it. However, this effect of apparent acceleration/deceleration was not significant in the LASCO FOV, which covers narrow elongation range. After the advent of truly wide-angle imaging with SMEI, Kahler & Webb (2007) developed a method to convert elongation to radial distance, by assuming that a CME feature can be considered as a point source moving radially outward in a fixed direction \( \phi_{FP} \) relative to an observer.
Figure 10. The left panel (marked as a) shows a tracked CME features in FP (open black dots) and HM (circles/filled black dots) model geometries. The right panel (marked as b) shows the tracked feature corresponding to the geometry of the SSE model (reproduced from Davies et al. 2012).

located at a distance $d_0$ from the Sun (Figure 10a). Using this concept, elongation ($\epsilon(t)$) variation of a moving CME feature can be converted to distance ($R_{FP}(t)$) from the Sun. With these assumptions, the following expression can be derived (Kahler & Webb 2007):

$$R_{FP}(t) = \frac{d_0 \sin(\epsilon(t))}{\sin(\epsilon(t) + \phi_{FP})}. \quad (2)$$

The fixed radial direction of the propagation of the CME can be determined using the source region of the CME. Also, the initial direction of propagation of a CME can be derived from the 3D reconstruction techniques applicable to COR observations and can be used in Equation (2). One major drawback of the FP method is that it does not take into account the finite cross-sectional extent of a CME.

**Harmonic mean method** To convert elongation angle to radial distance from the center of the Sun, Lugaz et al. (2009) assumed that a CME can be represented as a self-similarly expanding sphere attached to Sun-center with its apex traveling in a fixed radial direction. They further assumed that an observer measures the scattered emission from that portion of the sphere, where the line of sight intersects tangentially (Figure 10a). Based on these assumptions, they derived the distance ($R_{HM}$) of the apex of the CME from Sun-center as a function of elongation. They found that this distance is the Harmonic mean (HM) of the distances estimated using the FP and PP methods. Hence, the method is referred as HM method. The distance ($R_{HM}$) of the apex of the sphere from the Sun can be estimated by Equation (3) (Lugaz et al. 2009). In the equation, $\phi_{HM}$ is the radial direction of propagation of CME from the Sun-observer line, $\epsilon$ is elongation angle and $d$ is the distance of the observer from the Sun:

$$R_{HM}(t) = \frac{2d_0 \sin(\epsilon(t))}{1 + \sin(\epsilon(t) + \phi_{HM})}. \quad (3)$$

Although the spherical geometry of CMEs is included in the HM method, the assumption of such geometry may not be valid at much larger distances from the Sun because of the possible flattening of the CME front during its interaction with the ambient solar wind. The method has been used by Mishra et al. (2014), where they show that the HM method (based on a propagation direction retrieved from 3D reconstruction of COR2 data) performs better than PP and FP methods.

**Self-similar expansion method** Self-similar expansion (SSE) method represents the elongation variation as a function of time of a CME viewed from a single vantage point (Davies et al. 2012). In this method, a CME considered to have a circular cross-section in the plane corresponding to the position angle (PA) of interest, is not anchored to the Sun and, during its propagation away from the Sun, its radius increases such that it always subtends a fixed angle to the Sun center (see Figure 10b). They also showed that the SSE geometry can be characterized by an angular half-width ($\lambda$) and in its extreme forms, the SSE geometry is equivalent to the FP ($\lambda = 0^\circ$) and HM methods ($\lambda = 90^\circ$). It must be noted that $\lambda$ can also be considered as a parameter related to the curvature of the CME front. The distance ($R_{SSE}$) of a feature using this method at a certain elongation measured from STEREO-A or STEREO-B can
be calculated from the Equation (4) (Davies et al. 2012):
\[
R_{SSE}(t) = \frac{d_0 \sin(\epsilon(t))(1 + \sin(\lambda))}{\sin(\epsilon(t) + \phi_{SSE}) + \sin(\lambda)}. \tag{4}
\]

In all the single spacecraft methods described above, i.e., FP, HM and SSE, it is assumed that a CME propagates along a fixed radial trajectory (estimated in COR FOV), ignoring real or ‘artificial’ (see later) heliospheric gates along a fixed radial trajectory (estimated in COR). However, to make the calculation simpler, one can consider the launch time at the Sun’s center (Möstl et al. 2011). Theoretical elongation variation obtained from Equation (5) can be fitted to match closely with the observed elongation variation for an observed CME by finding the most suitable physically realistic combinations of \(v_{FP}\), \(\phi_{FP}\) and \(t_{FP}\) values. This approach to find the direction of propagation of a CME and its speed is called the fixed-phi-fitting (FPF) method. This method has been applied to transients like CIRs (Rouillard et al. 2008) and also on CMEs (Davis et al. 2009; Robbrecht et al. 2009; Mishra et al. 2014).

Harmonic mean fitting method Based on HM approximation (Lugaz 2009) for CMEs, an expression for the variation of elongation angle with time can be obtained (Lugaz 2010). Furthermore, following the fitting version of FP method, i.e., FPF, another new fitting version of HM method (i.e., Harmonic mean fitting, HMF) has been developed (Möstl et al. 2011). In HMF method, the time-variation of elongation angle (\(\epsilon\)) for a CME of constant speed (\(v_{HM}\)) propagating along a fixed radial direction (\(\phi_{HM}\)) can be written as Equation (6) (Möstl et al. 2011):
\[
\epsilon(t) = \arccos \left( \frac{-b + a \sqrt{a^2 + b^2} - 1}{a^2 + b^2} \right). \tag{6}
\]

In this equation, \(a\) and \(b\) are represented as:
\[
a = \frac{2d_0}{v_{HM}} - \cos(\phi_{HM}) \quad \text{and} \quad b = \sin(\phi_{HM}).
\]

It must be noted that in case of a limb CME, its flank will be observed in HI FOV because of the Thomson scattering surface. The flank of a CME is relatively closer to the Sun than its apex. HMF method accounts for this effect and estimates the propagation direction always farther away from the observer compared to the direction derived by FPF method.

Self-similar expansion fitting method Following the trend of FPF and HMF methods as described above, Davies et al. (2012) derived a method to convert the measured elongation of an outward moving feature into distance based on selection of an intermediate geometry for the CMEs. In the fitting version of the SSE (SSEF) method, the time-variation of elongation angle of a CME can be expressed in Equation (7) (Davies et al. 2012):
\[
\epsilon(t) = \arctan \left( \frac{v_{FP}(t) \sin(\phi_{FP})}{d_0 - v_{FP}(t) \cos(\phi_{FP})} \right). \tag{5}
\]
In this equation, $a$, $b$ and $c$ are represented as:

$$a = \frac{d_0(1 + c)}{v_{SSE}t} - \cos(\phi_{SSE}); \quad b = \sin(\phi_{SSE}); \quad \text{and} \quad c = \pm \sin(\lambda_{SSE}).$$  \hspace{1cm} (8)

It must be highlighted that FPF and HMF techniques can be used to estimate only the propagation direction, speed and launch time of the CMEs, while SSEF can estimate the additional angular half-width ($\lambda_{SSE}$) of CMEs. Thus, implementation of the SSEF technique requires a four-parameter curve fitting procedure with the assumptions that $\phi_{SSE}$, $v_{SSE}$ and $\lambda_{SSE}$ are constant over the complete duration of the time-elongation profile. The $\lambda_{SSE}$ measures the angular extent of the CME in a plane orthogonal to the observer’s FOV. If the SSEF is applied to the front, i.e., the apex of CMEs, then the positive form of $c$ is used, while for the trailing edge of the CMEs, its negative form is used. Hence, for CMEs propagating in certain directions, identification of correct form of equation to use is very important. It has been pointed out that in the case where SSEF can be applied to time-elongation profiles of features at the front and rear of a CME, then their fitted radial speed would differ, while other fitted parameters would be the same (Davies et al. 2012). In the SSEF method, the uncertainties arising from the degrees of freedom associated with the four-parameter fit could also be solved by putting constraints on the other parameters, like $\phi_{SSE}$, $\lambda_{SSE}$ and $v_{SSE}$ to reduce the number of free parameters in the fit. Again, we must emphasize that FPF and HMF methods are the special cases of SSEF method corresponding to $\lambda = 0^\circ$ and $\lambda = 90^\circ$, respectively.

In a comparison of performance of fitting methods, it was found that there is a large error in the estimated directions when these methods are applied to slow or decelerating CMEs. This is most likely due to a breakdown in their inherent assumptions of constant speed and direction (Mishra et al. 2014). They also show that HMF and SSEF methods predict more accurate arrival time and transit speed at L1 than that by FPF method. The main advantage of using FPF, HMF and SSEF methods is that these fitting methods are simple and quick to apply in real-time (Möstl et al. 2014; Mishra et al. 2014). In addition, these methods can be used for single spacecraft HI observations, i.e., when any one of STEREO spacecraft suffers from a data gap. However, a major disadvantage of these fitting methods is that they assume a constant speed and direction of propagation of the CMEs.

### 3.3.4 Multiple spacecraft reconstruction methods

Reconstruction methods can be greatly improved by using simultaneous observations from two different viewpoints. The STEREO spacecraft pair, until the loss of STEREO-B in 2014, has provided an ideal platform for such studies as it provided two identical instrument suites at the two different viewpoints. Several twin spacecraft reconstruction methods have been developed to determine the 3D characteristics of CMEs using the time-elongation profiles of the features of a CME from observations from both STEREO-A and STEREO-B viewpoints. These reconstruction methods utilizing observations of the same CMEs from multiple viewpoints can also be applied on the observations taken from different pairs of wide-angle imagers, e.g., SOHO/LASCO and STEREO/HI, SOHO/LASCO and SO/HI, PSP/WISPR, SO/HI, etc. However, far from the Sun, it is difficult to assume that the same feature of a CME can be observed from different viewpoints or even at different locations in the heliosphere. This increases the complexity of the stereoscopic reconstruction techniques and leads to their inherent limitations. The methods which have been widely used in the literature primarily using observations of heliospheric imagers (HIs) onboard twin STEREO-A and STEREO-B are described below.

**Geometric triangulation method** Based on the concept of triangulation among the two viewpoints of STEREO and a CME feature point, a stereoscopic method named as geometric triangulation (GT) method has been developed (Liu et al. 2010a). The GT method assumes that the same feature of a CME can be observed from two different viewpoints and that the difference in measured elongation angles for the tracked feature from STEREO-A and STEREO-B is entirely due to two viewing directions. Using imaging observations and a Sun-centered coordinate system, the elongation angle of a moving feature can be calculated in consecutive images. The details of the GT method in an ecliptic plane applicable for a feature propagating between the two spacecrafts have been explained in earlier studies (Liu et al. 2010a, b). A schematic diagram for the location of the twin spacecraft and the tracked feature is shown in Figure 11. Using this geometry, Liu et al. (2010a) derived the following equations:

$$d_A = \frac{r \sin(\alpha_A + \beta_A)}{\sin \alpha_A},$$  \hspace{1cm} (9)
in Figure 11) will be nearly symmetrically located from both view directions (lines-of-sight AP and BP as shown taken into account. However, for Earth-directed events, Thomson scattering and the geometry of CMEs are not the Sun–Earth line. Therefore, the scattering angles for a CME feature moving in the direction of the arrow and STEREO-B viewpoints (adapted from Mishra & Srivastava 2013).

\[
d_B = \frac{r \sin(\alpha_B + \beta_B)}{\sin \alpha_B},
\]

\[
\beta_A + \beta_B = \gamma.
\]

In the above equations, \( r \) is the radial distance of the feature from the Sun, \( \beta_A \) and \( \beta_B \) are the propagation angles of the feature relative to the Sun-spacecraft line. \( d_A \) and \( d_B \) are the distances of the spacecraft from the Sun and \( \gamma \) is the longitudinal separation between the two spacecrafts. Once the elongation angles (\( \alpha_A \) and \( \alpha_B \)) are derived from imaging observations, the above equations can be solved for \( \beta_A \):

\[
\beta_A = \arctan \left( \frac{\sin(\alpha_A) \sin(\alpha_B + \gamma) - f \sin(\alpha_A \sin(\alpha_B))}{\sin(\alpha_A) \cos(\alpha_B + \gamma) + f \cos(\alpha_A \sin(\alpha_B))} \right),
\]

where \( f = d_B/d_A \) (\( f \) varies between 1.04 and 1.13 during a full orbit of the STEREO spacecraft around the Sun). Using Equation (12), the propagation direction of a CME can be estimated. Once, the propagation direction has been estimated, the distance of the moving CME feature can be estimated using Equation (9).

In the GT reconstruction method, the effects of Thomson scattering and the geometry of CMEs are not taken into account. However, for Earth-directed events, both view directions (lines-of-sight AP and BP as shown in Figure 11) will be nearly symmetrically located from the Sun–Earth line. Therefore, the scattering angles (\( \chi_A \) and \( \chi_B \)) for both observers will only be slightly different and the resulting difference in the received scattered light intensity for both observers (STEREO-A and STEREO-B) will be small. The approximation that both observers view the same part of CME may not be true when Earth-directed CMEs are at a large distance from the Sun (for view directions AX and BY as shown in Figure 11) and also near the Sun for very wide or rapidly expanding CMEs. It is also rather unlikely that the same feature of a CME will be tracked in each successive image. In light of the aforementioned points, it is clear that the geometry of the CME should be taken into account in any of the reconstruction methods. However, the breakdown of idealistic assumptions about the geometry can result in new errors in the estimated kinematics.

Tangent to a sphere method Following the development of GT method (Liu et al. 2010a), another stereoscopic method named as tangent to a sphere (TAS) (Lugaz et al. 2010) was proposed for the reconstruction of CMEs using HI observations. The TAS method assumes that the CME has a circular cross-section anchored at the Sun and twin STEREO observe the tangent to the circular CME front, in contrast to the assumption made in the GT method that the CME is a point. Hence, the observers from two viewing locations of STEREO do not observe the same CME feature. Under HM approximation, the measured diameter (i.e., \( R_A \) and \( R_B \)) of the CME from STEREO-A and STEREO-B, respectively, can be solved for \( R_A = R_B \). The expressions for \( R_A \) and \( R_B \) are given in Equations (13) and (14), respectively (Lugaz et al. 2010):

\[
R_A = \frac{2d_A \sin(\alpha_A)}{1 + \sin(\alpha_A + \beta_A - \phi_{TAS})},
\]

\[
R_B = \frac{2d_B \sin(\alpha_B)}{1 + \sin(\alpha_B + \beta_B + \phi_{TAS})}.
\]

In the above Equations (13) and (14), the parameters \( d, \alpha, \beta \) and \( \phi_{TAS} \) are the distance of observer from the Sun, elongation angle, separation angle of observer from the Sun–Earth line and propagation direction of CME from the Sun–Earth line, respectively. The \( \phi_{TAS} \) is considered positive in westward direction from Sun–Earth line. The solution of these equations for \( \phi_{TAS} \) can be used to estimate the propagation direction of the CMEs. This method to calculate the kinematics of the CME was referred as tangent-to-a-sphere (TAS) method. This method assumes that measured elongation angle refers to the point where the observers’ line of sight intersects tangentially to the spherical front of the CME.
It is also noted that different reconstruction methods, based on different assumptions, often provide different kinematics and arrival time estimates for the CMEs. Therefore, attempts to assess the relative performance of several 3D reconstruction methods applicable to HI observations for estimating the arrival time of CMEs, have been made (Lugaz 2010; Howard 2011; Mishra et al. 2014; Mishra & Srivastava 2015). Mishra et al. (2014) showed that the stereoscopic methods (as described in Section 3.3.4) are more accurate than single spacecraft methods (as described in Section 3.3.2) for the prediction of CME arrival times and speeds at L1. Irrespective of the characteristics of the CMEs, among the three stereoscopic methods, such as GT, TAS and SSSE as described before, the TAS method gives the best prediction of transit speed and arrival time within 8 h for fast CMEs and 17 h for slow or fast decelerating CMEs. It is also found that the HM method (based on a propagation direction retrieved from 3D reconstruction of COR2 data) performs best among the single spacecraft techniques. Independent of the characteristics of the CMEs, Mishra et al. (2014) have shown that the HMF and SSF single spacecraft fitting methods perform better than FPF. All three fitting methods give reasonable arrival time predictions for the fast speed CME that undergoes no discernible deceleration. However, for the slow CME and the fast, but decelerating CME, the fitting methods are only accurate within 30 h in terms of their arrival time prediction and yield relatively larger errors (up to hundreds of km s\(^{-1}\)) in predicted speed.

3.4 Drag based model for propagation of CMEs

In both the pre- and post-STEREO era, the kinematics of the CME near the Sun has been used either as input to the drag-based model (DBM) or the kinematics is extrapolated to find the arrival time of CMEs at Earth (Cargill 2004; Manoharan 2006; Davis et al. 2009; Byrne et al. 2010; Mishra & Srivastava 2013; Subramanian et al. 2014). The DBM is often used assuming that the Lorentz and gravity forces decrease such that the drag force can largely govern CME dynamics far from the Sun. Although it is not proven that drag is the only force that shapes CME dynamics in the interplanetary medium, the observed deceleration/acceleration of some CMEs has been closely reproduced by considering only the drag force acting between the CME and the ambient solar wind medium (Lindsay et al. 1999; Cargill 2004; Manoharan 2006; Vršnak et al. 2009; Lara & Borgazzi 2009). In the STEREO era, with the formulation of several 3D reconstruction methods, the 3D
kinematics of CMEs estimated in COR2 and HI FOV is used to estimate their arrival time at Earth (Mishra & Srivastava 2013; Mishra et al. 2014, 2015a). In these studies, the DBM of Vršnak et al. (2013) is used to derive the kinematic properties. The DBM is used only for the distance range during which a CME could not be tracked in the J-maps constructed from HIs observations.

The DBM model assumes that, after 20 $R_\odot$, the dynamics of CMEs is solely governed by the drag force and that the drag acceleration has the form, $a_d = -\gamma (v - w)(v - w)$, (see Cargill et al. 1996; Cargill 2004; Vršnak et al. 2010), where $v$ is the speed of the CME, $w$ is the ambient solar wind speed and $\gamma$ is the drag parameter. The drag parameter is given by $\gamma = (c_d A \rho_w )/(M + M_v)$, where $c_d$ is the dimensional drag coefficient, $A$ is the cross-sectional area of the CME perpendicular to its propagation direction (which depends on the CME-cone angular width), $\rho_w$ is the ambient solar wind density, $M$ is the CME mass and $M_v$ is the virtual CME mass. The latter is written as, $M_v = \rho_w V/2$, where $V$ is the CME volume. A statistical study has shown that the drag parameter generally lies between 0.2 $\times$ 10$^{-7}$ and 2.0 $\times$ 10$^{-7}$ km$^{-1}$ (Vršnak et al. 2013). They assumed that the mass and angular width of CMEs do not vary beyond 20 $R_\odot$ and also showed that the solar wind speed lies between 300 and 400 km s$^{-1}$ for slow solar wind conditions. For the case, where a CME propagates in high speed, solar wind or if a coronal hole is present in the vicinity of the CME source region, the ambient solar wind speed should be chosen to lie between 500 and 600 km s$^{-1}$, along with a lower value of the drag parameter.

The DBM can be run instantly, which can provide the prediction of ICME expansion and arrival time at any heliospheric locations in the ecliptic plane. It is shown that using a typical value for solar wind speed, the DBM estimate the CME arrival time with typical errors of only around 12 h (Vršnak et al. 2013). We note that DBM ideally assumes that the CME is propagating into an isotropic ambient solar wind. Considering the fact that a CME has actually a 3D structure spanning over different longitudes and latitudes, it is possible that parts of the CME at different latitudes and longitudes are influenced by solar wind of different speeds. One can expect that the high-speed wind from coronal holes may strongly affect those parts of the CME, which are at higher latitudes. It may also be the case that a CME experience solar wind of different speeds during the different segments of their heliospheric journey. Such a scenario can arise in the cases when a fast CME encounters a slow CME that was launched earlier in the same direction.

It is possible that the performance of DBM and thus, typical errors in predicting the arrival time of different portions of the CMEs can be reduced by improving the drawbacks of the simplified DBM.

3.5 Arrival time of CMEs at the Earth

STEREO observations have greatly enhanced our ability to continuously track CMEs. This is because of STEREO’s two viewpoints that allow the 3D reconstruction of CMEs. In an attempt to combine the observed CME kinematics with a model, Kilpua et al. (2012) estimated the 3D speed of CMEs using coronagraphic observations and used it into the CME travel-time prediction models of Gopalswamy et al. (2000a, 2001a). They compared the estimated travel time with the actual travel time of CME from the Sun to STEREO, ACE and WIND spacecraft. They also compared the estimated travel time with that estimated using the projected CME speed into the models. Their study shows that CME 3D speeds give slightly ($\approx$ 4 h) better predictions than projected CME speeds. However, in their study, a large average error of 11 h is noted between the predicted and observed travel times.

The large FoV of HIs onboard STEREO enables the tracking of CMEs to a much larger distance in the heliosphere. Using STEREO observations, several attempts have been made to understand the 3D propagation of CMEs and estimate their arrival time (Kahler & Webb 2007; Mierla et al. 2009; Srivastava et al. 2009; Liu et al. 2010a; Möstl et al. 2011; Davies et al. 2012, 2013). In a recent study, a CME was tracked beyond the Earth’s distance and was shown that a proper treatment of CME geometry must be performed in estimating CME kinematics, especially when a CME is directed away from the observer (Liu et al. 2013). Using different reconstruction methods on HI observations, Möstl et al. (2014) shows an absolute difference between predicted and observed CME arrival times of 8.1 ± 6.3 h. These studies have shown that longer tracking of CMEs using HI observations is necessary for improved understanding of their evolution in the heliosphere.

To understand the heliospheric evolution of CMEs from the Sun to Earth, the kinematics of several CMEs have been estimated by implementing suitable 3D reconstruction methods to remote sensing observations of CMEs (Mishra & Srivastava 2013). These studies suggested that the use of reconstruction methods on HI data combined with DBM gives a better prediction of the CME arrival time than using only 3D speed estimated in COR FOV. Thus, near-Sun 3D speed of CMEs with an assumption that the speed remains constant up
to L1, cannot accurately predict the arrival time for a majority of CMEs. Sometimes CMEs are observed to erupt in quick succession and, under certain favorable initial conditions, can interact or merge with each other during their propagation in the heliosphere (Harrison et al. 2012). Therefore, the interaction of CMEs in the heliosphere is expected to be more frequent near the solar maximum. In the STEREO era, focus of the studies has been to understand the propagation of multiple CMEs following one another from the Sun to the Earth and their consequences on hitting the Earth’s magnetosphere.

The HI observations have helped to witness several cases of interacting CMEs. Many attempts have been made to understand CME–CME interaction at a range of distances from the Sun using SECCHI/HI observations (Harrison et al. 2012; Lugaz et al. 2012; Möstl et al. 2012; Temmer et al. 2012). It has been shown that during the interaction of CMEs, their kinematics may change. Therefore, such interactions complicate the problem of estimating their arrival time, and any space weather prediction scheme estimating the arrival time of interacting CMEs must take their post-interaction kinematics into account. Therefore, it is important to understand the nature of CME–CME collision by measuring the energy and momentum exchange during the collision/interaction of CMEs.

The actual arrival time of remotely tracked CMEs at Earth can be marked using in situ observations near 1 AU. The actual arrival time of some geoeffective CMEs can also be inferred by monitoring the geomagnetic perturbations. These actual arrival times can be compared with the arrival times estimated based on the kinematics obtained from reconstruction methods. However, the identification of a CME in in situ observations is not straightforward. The difficulty in the identification further increases when the CMEs arrive as structures formed due to interaction or collision of several CMEs (Burlaga et al. 2001). As they interact, they experience a change in their plasma, dynamic and magnetic field parameters. Hence, the collision of CMEs may lead to a new type of solar wind structure, which is expected to show different in situ signatures than the signatures of isolated CMEs. In addition, such new structures might have a different geomagnetic response as compared to isolated CMEs described in Section 2.1.2.

In addition, the interaction or collision of successive CMEs can, in some cases, produce an extended period of southward $B_z$ and cause strong geomagnetic storms (Farrugia et al. 2006). The geomagnetic responses of interacting CMEs have been explored in several studies described in Section 3.6. In addition, studies have been devoted in understanding the arrival time, in situ identification of interacting CMEs at 1 AU, and various plasma processes during the interaction of CMEs that can change the initial identity and properties of CME plasma. In the STEREO era, by exploiting the Sun to Earth remote observations of CMEs from twin viewpoints, one expected to have better success in predicting the speed and direction of a CME near the Earth. However, from space weather perspectives, without the knowledge about negative $B_z$ component of CME, it would remain difficult to predict the intensity of resulting geomagnetic storms well in advance.

3.6 CME–CME interaction

The possibility of CME–CME interaction has been reported much earlier by analyzing in situ observations of CMEs by Pioneer 9 spacecraft (Intriligator 1976). The compound streams (interaction of CME–CIR or CME–CME) were first inferred by Burlaga et al. (1987) using observations from Helios and ISEE-3 spacecraft. They showed that such compound streams formed due to interactions have amplified parameters responsible for producing major geomagnetic storms. Using wide FoV coronagraphic observations from LASCO and long-wavelength radio observations, Gopalswamy et al. (2001c) provided for the first time evidence for CME–CME interaction. Burlaga et al. (2002) identified a set of successive halo CMEs directed toward the Earth and found that they appeared as complex ejecta near 1 AU (Burlaga et al. 2001). They inferred that these CMEs launched successively, merged en route from the Sun to Earth and formed complex ejecta in which the identity of individual CMEs was lost. Thus, these interactions are of great importance from the space weather point of view.

It has also been shown that CME–CME interactions are important as they can result in an extended period of enhanced southward magnetic field, which can cause intense geomagnetic storms (Farrugia et al. 2006). Such interactions help to understand the collisions between large scale magnetized plasmoids and hence, various plasma processes involved. Also, if a shock from a following CME penetrates a preceding CME, it provides a unique opportunity to study the evolution of the shock strength and structure and its effect on preceding CME plasma parameters (Lugaz et al. 2005; Möstl et al. 2012; Liu et al. 2012).

Estimating the accurate kinematics and arrival time of CMEs at Earth is crucial for predicting space weather effects. Since CME–CME interactions are responsible for changing the kinematics of interacting CMEs, such
interactions need to be examined in detail. Furthermore, as the subset of CMEs are identified as MCs, which are flux-rope structures, the reconnection between magnetic flux ropes can be explored by studying cases of CME–CME interactions (Gopalswamy et al. 2001c; Wang et al. 2003). Such reconnection in CME–CME interaction are known to lead to solar energetic particles (SEPs) events (Gopalswamy et al. 2002). Wang et al. (2003) have shown that a forward shock can cause an intense southward magnetic field of long duration in the preceding MC. Such modifications in the preceding cloud are important for space weather prediction.

It was realized well before the era of wide-angle imaging far from the Sun that CME–CME and CME–shock interactions are important candidates to be studied from physics and space weather prediction point of view. In pre-STEREO era, the understanding of involved physical mechanisms in CME–CME or CME–shock interaction was achieved mostly from magnetohydrodynamic (MHD) numerical simulations of the interaction of a shock wave with a magnetic cloud (MC) (Vandas et al. 1997; Vandas & Odstrcil 2004; Xiong et al. 2006), the interaction of two ejecta (Gonzalez-Esparza et al. 2004; Lugaz et al. 2005; Wang et al. 2005) and the interaction of two MCs (Xiong et al. 2007, 2009). However, only a few attempts could be made to understand the CME–CME interaction using imaging observations near the Sun (Gopalswamy et al. 2001c) and in situ observations near the Earth (Burlaga et al. 2001).

In the STEREO era, the twin spacecraft observations enabled to determine the 3D locations of CMEs features in the heliosphere and hence, provide direct evidence of CME–CME interaction using images from heliospheric imagers. However, immediately after the launch of STEREO, during deep extended solar minimum, not many interacting CMEs were observed. As the solar cycle 24 progressed, CME interaction appeared to be a fairly common phenomenon, in particular around solar maximum.

In STEREO era, several cases of interacting CMEs in the inner heliosphere have been extensively studied using observations and numerical simulations to understand the physical processes occurring during CME–CME interaction. For example, the interacting CMEs of 1 August 2010 have been studied by several researchers using primarily the STEREO/HI (white-light imaging), near-Earth in situ and, STEREO/waves radio observations (Harrison et al. 2012; Liu et al. 2012; Möstl et al. 2012; Temmer et al. 2012; Martínez Oliveros et al. 2012; Webb et al. 2013). These studies have shown that CME–CME interaction can lead to change in the properties of CMEs, such as their propagation speed, size, expansion speed, direction of propagation, temperature, internal magnetic field, etc. Therefore, understanding such interactions/collisions of CMEs are important for accurate space weather forecasting. Using STEREO imaging observations, several key questions that are not well understood regarding CME interaction have been addressed:

1. How do the dynamics of CMEs change after interaction? What is the regime of interaction, i.e., elastic, inelastic, or super-elastic (Lugaz et al. 2012; Shen et al. 2012b; Mishra & Srivastava 2014; Mishra et al. 2015a, 2016, 2017)?
2. What are the consequences of the interaction of CME–shock structure? How does the overtaking shock change the plasma and magnetic field properties of the preceding magnetic cloud (Lugaz et al. 2005, 2012; Liu et al. 2012)?
3. What are the favorable conditions for the merging of CMEs and the role of magnetic reconnection in it (Gopalswamy et al. 2001c)?
4. What is the possibility for the production of a reverse shock at the CME–CME interaction site (Lugaz et al. 2005)?
5. Do these interacted structures produce different geomagnetic consequences than individual CMEs, on their arrival to magnetosphere (Farrugia et al. 2006)?
6. What are the favorable conditions for the deflection of CMEs and enhanced radio emission during CME–CME interaction (Lugaz et al. 2012; Martínez Oliveros et al. 2012)?

To understand the interaction of CMEs, a study of Mishra & Srivastava (2014) investigated the signatures of three interacting CMEs in remote sensing and in situ observations. These three CMEs were observed to have launched from the Sun successively on 13–15 February 2011. These three CMEs are named as CME1, CME2 and CME3, respectively. Based on the initial 3D speed and direction of these three CMEs in COR2 FOV, it was evident that they may interact in the interplanetary medium. CME3 was found to be the fastest among all three CMEs and shows a strong deceleration in the COR2 FOV because of the preceding CME2 which acted as a barrier. Mishra & Srivastava (2014) investigated the kinematics of the CMEs in the heliosphere using stereoscopic methods. They noted that a collision between CME3 and CME2 took place around 24–28 $R_\odot$. As CME1 was faint and could not be tracked up to HI2 FOV in J-maps, they inferred, based on the extrapolation of distances, that CME2 caught up with
Figure 13. From top to bottom, the panels show the distance, propagation direction and speed (as obtained using SSSE method) of the leading edge (LE) of CME1 (blue), CME2 (black) and CME3 (red). CME1, CME2 and CME3 were launched on 13, 14 and 15 February 2011, respectively. The horizontal dashed line in the top panel marks the heliocentric distance at the L1 point. The dashed horizontal line in the middle panel marks the Sun–Earth line. The speed shown with symbols is estimated from the differentiation of distance points using three-point Lagrange interpolation. The speed shown with the solid line is determined by differentiating the fitted first-order polynomial for estimated distance for each 5-h interval. From the left, the first and second vertical dashed lines mark the start and end of the collision phase, respectively, for the collision of CME3 and CME2. In the top panel, the rightmost vertical dashed line marks the inferred interaction between CME2 and CME1. The vertical solid lines at each data point show the error bars (adapted from Mishra & Srivastava 2014).

CME1 between 138 and 157 $R_\odot$. The kinematics of these three CMEs before and after their interaction is shown in Figure 13. These CMEs were also studied in detail by Maričić et al. (2014) using single spacecraft reconstruction methods.

The study of Mishra & Srivastava (2014) identified signatures of collision between CMEs in the kinematics profiles as an exchange in their speed. They, under a head-on collision scenario, analysed momentum and energy exchange during the collision phase of CME2 and CME3. They found that collision was close to elastic, as the coefficient of restitution ($e$) was found to be 0.9. However, in another study of the same CMEs, Mishra et al. (2017) considered an oblique collision scenario for CME2 and CME3, and found a coefficient of restitution ($e$) of 1.65. This probably suggests that assumption of head-on collision scenario underestimates the value of the coefficient of restitution.

The in-situ observations, arrival time and geomagnetic response of interacting CMEs of 13–15 February 2011 (CME1, CME2 and CME3) were also studied in Mishra & Srivastava (2014). They identified three CMEs as three distinct regions in in situ observations near 1 AU. The in situ observations revealed that CME2 is overheated at $\approx 10^6$ K, perhaps because it is squeezed between CME1 and CME3. CME2, showing a high speed at the front and low speed at its trailing edge, reveals a signature of fast expansion, which was interpreted possibly due to magnetic reconnection at the CME's front edge (Maričić et al. 2014). Such signatures of compression and heating due to CME–CME interaction and passage of CME driven shock through the preceding CME have also been reported in earlier studies (Lugaz et al. 2005; Liu et al. 2012; Temmer et al. 2012). In situ data also revealed a smaller spatial scale of CME1 and CME2 than CME3. This is possibly due to the compression of preceding CMEs by the following CME or shock. There are also other studies on CME–CME interaction, which have shown that interacting CMEs appear as complex ejecta in in situ observation and each interacting CME may not be identified as a separate entity (Liu et al. 2014; Lugaz & Farrugia 2014; Mishra & Srivastava 2014; Mishra et al. 2015b, 2017).

Mierla et al. (2010) and Mishra et al. (2017) considered the propagation and expansion speeds, impact direction, and angular size as well as the masses of the CMEs to understand the CME–CME interaction. For the first time, they examined the nature of collision of eight cases of interacting CMEs by carrying out the analysis in 3D scenarios. Among the eight cases, they showed that the nature of collisions was perfectly inelastic for two cases, inelastic for two cases, elastic for one case and super-elastic for three cases. The study established that the crucial pre-collision parameters of the CMEs responsible for increasing the probability of a super-elastic collision are, in descending order of priority, their lower approaching speed, expansion speed of the following CME higher than the preceding
one and a longer duration of the collision phase. This important finding is in agreement with the simulation studies (Shen et al. 2016). Therefore, it is worth to investigate further the nature of the collision and the processes responsible for magnetic and thermal energy conversion to kinetic energy to make a collision super-elastic.

The observational studies on collision dynamics suffer from uncertainties due to adopted boundary for the start and end of the collision phase (Mishra et al. 2016, 2017). This is because of difficulty in defining the start of collision as the following CME starts to decelerate (due to its interaction with preceding CME) and preceding CME starts to accelerate before (most possibly due to shock driven by following CME) they both are actually observed to merge. Hence, different timing and large time-interval of acceleration of one CME and deceleration of the other, prevent to pinpoint the exact start and end of the collision phase. Furthermore, the total mass of CMEs is used to study their collision dynamics, but as the CME is not a solid body therefore, its total mass is not expected to participate in the collision. Keeping in mind the limitations on the study of CME–CME interaction, further work is required to understand the CME–CME interaction by incorporating various plasma processes.

The geomagnetic response of interacting CMEs has also been investigated extensively in several studies (Farrugia et al. 2006; Mishra & Srivastava 2014; Mishra et al. 2015a; Lugaz & Farrugia 2014). The study of Mishra & Srivastava (2014) does not favor the possibility of strengthening the geomagnetic response as a consequence of the arrival of two or more interacting CMEs at Earth. However, in another study (Mishra et al. 2015a), the interaction region (IR) formed due to the collision between two CMEs, is associated with intensified plasma and magnetic field parameters, which were responsible for major geomagnetic activity. The in situ measurements of interacting CMEs near 1 AU shows that they are accelerated or decelerated during the interaction, compressed and heated.

The arrival times of interacting CMEs at Earth were also estimated based on HIs observations (Mishra et al. 2015a). From the arrival time estimates, it was noticed that arrival time estimation of interacting CMEs improves by few (up to 10 h) hours when the post-collision speeds are used instead of pre-collision speeds. The estimated post-collision kinematics of interacting CMEs is crucial to be combined with DBM to improve the arrival time estimation of the interacting CMEs. Thus, several studies in the STEREO era reveal that tracking of CMEs up to large heliospheric distances is necessary for better understanding of the CME–CME interaction and the prediction of their arrival time at the Earth. Thus, CMEs cannot be treated as completely isolated magnetized plasma blobs, especially when they are launched in quick succession. Each preceding CME offers a different background medium to the following CMEs, which should also be taken into account, while studying the propagation of CMEs. From the survey of literature (Webb et al. 2012; Harrison et al. 2017), it is obvious that the prediction of arrival time of CMEs, especially interacting CMEs, and association between remote and in situ observations of CMEs, are challenging even in the era of STEREO, where CMEs can be imaged continuously from near the Sun to near the Earth.

4. Summary and future directions

The speed, direction, mass and morphology of a CME at a particular location in the heliosphere can be studied by analyzing remote sensing observations, while the temperature, speed, density, magnetic field, composition and charge states of CME plasma/solar wind can be measured from in situ observations. By the time a CME reaches the spacecraft hosting the instrumentation for in situ measurements, it has already evolved and therefore, the plasma parameters are different than measured remotely (Crooker & Horbury 2006). However, if the physics of evolution of a CME is known, then its properties estimated remotely can be extrapolated up to the location of in situ spacecraft to make a comparison between both sets of observations with reasonable accuracy. In the absence of a complete understanding of the true nature of the evolution of CMEs, it is often difficult to predict their arrival time to the Earth based on their initial characteristics estimated from remote sensing observations made when still near the Sun. The CME characteristics estimated from remote observations suffer from the line of sight integration and projection effects, while CME’s plasma parameters can be measured along a specific trajectory through the CME by the in-situ spacecraft (Webb & Howard 2012). The uncertainties in the morphology and kinematics of CMEs due to projection effects, in white-light images from a single viewpoint, can be resolved by implementing appropriate 3D reconstruction techniques on the CME images from multiple viewpoints near and far from the Sun. The continuous spatial coverage of CMEs from the Sun to 1 AU distance was possible by the imaging instruments onboard twin STEREO spacecraft. One can unambiguously track a CME continuously from its lift-off in the
inner corona to almost the Earth by constructing $J$-maps (i.e., time-elongation maps) from STEREO/SECCHI images (Davis et al. 2009; Möstl et al. 2009). In the present review, a number of benefits of imaging a CME in the heliosphere from the off-Sun–Earth line have been discussed.

Earlier the STEREO era, it was already inferred that CMEs accelerate or decelerate till they obtain the speed of ambient solar wind medium. However, the analysis of several Earth-directed CMEs using the SECCHI/HI observations have helped witnessing such changes in the CME kinematics. Most of the studies in the STEREO era, have shown that determining the 3D speed of CMEs near the Sun and assuming that it remains constant for the remaining distance, i.e., up to 1 AU, is not sufficient to accurately predict the arrival time at Earth of the majority of CMEs (Harrison et al. 2012; Shen et al. 2012b; Temmer et al. 2014; Mishra et al. 2015a, 2017). This is true especially for a fast speed CME traveling in the slow solar wind environment or a slow speed CME traveling in the high speed stream. It is shown that the estimated 3D kinematics of CMEs used as inputs in DBM, improve the arrival time prediction of the CMEs at 1 AU. Thus, the role of drag forces, in the dynamics of CMEs, is effective farther out (few tens of solar radii) from the Sun. The studies have also shown that a CME may undergo non-radial longitudinal motion even far from the Sun, specially in the case of CME–CME interaction (Lugaz et al. 2012).

The interaction and/or collision of one CME with another CME has been thoroughly investigated in the STEREO era (Harrison et al. 2012; Shen et al. 2012b; Temmer et al. 2014; Mishra et al. 2015a, 2017). The studies have concluded that there is a significant exchange of momentum and kinetic energy during the collision of the CMEs. Therefore, post-collision kinematics of CMEs must be used for their improved arrival time prediction at 1 AU. It is also studied that collision/interaction of CMEs have significant effects on the magnetic and plasma parameters of both preceding and following CMEs. The formation of IR at the interface of interacting CMEs is found to be responsible for major geomagnetic activity (Mishra et al. 2015a). Therefore, the geomagnetic disturbances due to interacting CMEs need to account for the changes in CMEs parameters resulting from their interaction. Interacting CMEs can be commonly identified in in situ observations at 1 AU in the form of multiple-MC events, where individual CME can be distinguished, or they appear as a complex ejecta, where some of the characteristics of CMEs are lost with shocks propagating inside a previous CME. These structures have different ways to interact with Earth’s magnetosphere to give intense geomagnetic storms as compared to an isolated CME. The in situ observations at 1 AU shows only the plasma parameters after the CME–CME interaction, but not during the collision/interaction duration. The in-situ data from Solar Orbiter and Parker Solar Probe can provide the opportunities to measure the plasma parameters during the interaction process also.

Although HIs have provided the potential to improve the space weather forecasting, some CMEs become too faint to be tracked unambiguously and they impose difficulties in reliably predicting their propagation direction, arrival time and speed at 1 AU. Furthermore, the specific assumptions in some of the currently used reconstruction methods compromise the estimates of the complex evolution of the kinematics and morphology of CMEs. Such a complex heliospheric evolution of CMEs is due to their interactions with the ambient slow/fast solar wind, CIRs and other CMEs, which result in errors in the predicted arrival time of CMEs at Earth (Gopalswamy et al. 2009; Lugaz & Farrugia 2014; Mishra et al. 2015a). Thus, it is important to understand the conditions in the background solar wind and the level of preconditioning of interplanetary medium due to another large-scale solar wind structure, for accurate arrival time prediction of CMEs.

Given the limited success in arrival time prediction of CMEs, it is required to make several studies in this direction (Harrison et al. 2009; Mishra et al. 2014; Harrison et al. 2017). In this regard, it can be advantageous to compare the $J$-maps derived from the observations with the synthetic $J$-maps outputs from the MHD models. Using this comparison of real and synthetic $J$-maps, one can identify the difference in CME evolution in simulation and can eventually correct the model results. Moreover, the background solar wind simulated by the models using near-Sun conditions should be refined under the monitoring of other large scale heliospheric structures away from the Sun. It is important to point out that the model-run may provide several solutions under the inputs of different CME and background solar wind parameters. The large number (i.e., spread) in the solutions can be reduced to a small number by comparing it with real $J$-maps. A small number of solutions would then be suitable for predicting a reasonably accurate range of CME arrival times (Harrison et al. 2017). Thus, the heliospheric observations have the potential to contribute to operational space weather services.

The STEREO era has provided an opportunity to understand the association between remotely observed
CME structures and \textit{in situ} observations. However, the prediction of negative $B_z$ at Earth is most important for predicting the occurrence of geomagnetic storms (Gonzalez \textit{et al.} 1989; Srivastava & Venkatakrishnan 2002). Determination of the negative $B_z$ component in the CMEs by exploiting the remote sensing observations is far from reality. By examining the neutral line in the source region of a CME, one can attempt to guess the inclination of the flux rope, expected direction of rotation and the portion of flux rope, where negative $B_z$ may occur (Yurchyshyn \textit{et al.} 2005). Our understanding of the flux rope structure of a CME is very limited and it is still debated whether such flux ropes are formed during the eruption or exist before the eruption (Chen 2011). It is noted that although CME propagation and arrival time are the focus of several studies for long, using MHD models and observations, however, the crucial things for space weather prediction for magnetic storms are the direction and intensity of the magnetic field in both the ICMEs and upstream sheath. There are models used to estimate the magnetic field inside the ICMEs arriving at 1 AU; still, such models have not been independently and objectively tested for predictive purposes. There are also quite promising studies using machine learning algorithms to predict geomagnetic storms at 1 AU (Pricopi \textit{et al.} 2022). But again, one should properly test the reliability of such approaches. Thus, further work is required to understand the key issues responsible for space weather near the Earth.

The successful exploitation of heliospheric imagery can revolutionize our understanding of the evolution of CMEs. This have made researchers to include instruments similar to HIs on other space missions, such as SoloHI (Horbury \textit{et al.} 2020) on the Solar Orbiter (SO) (Müller \textit{et al.} 2020) and the Wide-field Imager for Solar PRobe (WISPR) (Vourlidas \textit{et al.} 2016) on the Parker Solar Probe (PSP) (Fox \textit{et al.} 2016). The orbital motion of STEREO has allowed heliospheric imaging from different heliospheric locations including their passage through the L4 and L5 Lagrangian points. With the progress of the STEREO mission, the separation between the twin spacecraft reached to 180$^\circ$ around the beginning of year 2011, and further they continued increasing their separation from the Sun–Earth line. These locations of STEREO, behind the Sun from Earth’s viewpoint, are less suitable for the heliospheric imaging of the Earth-directed CMEs. This is most importantly because an Earth-directed CME tend to lie outside the Thomson sphere and are poorly visible from these STEREO locations behind the Sun (Howard & DeForest 2012). Also, the communications with STEREO-B were lost around October 2014, which were re-established only in August 2016, and it has now been out of contact since September 2016. Although STEREO-A continues to operate normally, the loss of STEREO-B somewhat limited the operational potential of STEREO mission. The higher signal-to-noise imaging observations from heliospheric imagers onboard PSP and SO allow now, imaging of the inner and darker cavities instead of traditional tracking of bright fronts of CMEs/ICMEs using STEREO. The traditional heliospheric tracking of ICMEs in white-light imaging observations identifies the enhanced density structure, which is the compressed sheath region, whereas the \textit{in situ} observations accurately identify the density-depleted structure with the enhanced magnetic field, which is the magnetic ejecta or the flux rope. The flux rope structure of ICMEs appears as the darker cavity in the white-light imaging observations and therefore, the tracking of the darker cavity can enable to more accurately connect the remote sensing observations of ICMEs with their \textit{in situ} observations (Hess \textit{et al.} 2020; Horbury \textit{et al.} 2020; Rouillard \textit{et al.} 2020). Furthermore, observations from these new missions may change a few of the assumptions on the radial evolution of plasma parameters (i.e., density, magnetic field, etc.) in CMEs and solar wind, and therefore, it has the potential to refine the existing propagation models (empirical or MHD) of CMEs.

The STEREO/HI observations almost always have been used in conjunction with SOHO/LASCO observations to study the heliospheric evolution of CMEs. A similar approach should also be taken for the observations of PSP/WISPR, SoloHI and of the Metis coronagraph onboard SO. We expect that future studies will provide further insights by coordinated science campaigns with multiple space missions like SOHO, STEREO, SDO, PSP, SO and so on. The observations of a large number of CMEs at different heliocentric distances from the Sun by PSP and SO missions may help in validating the models of CME magnetic field forecasting. In a recent study of modeling the evolution of ICMEs, the researchers have observed the plasma parameters of the ICMEs by widely separated five \textit{in situ} spacecraft, SO, BepiColombo, PSP, Wind and STEREO-A, in connection with the remote observations of the same ICMEs by coronagraph and heliospheric imager onboard STEREO-A/SECCHI and SOHO/LASCO (Möstl \textit{et al.} 2022). Such studies on several cases, possible during the maximum phase of solar cycle 25, can improve understanding of the interplanetary evolution of ICMEs, their magnetic structure, global shape of their flux ropes and shocks. Further, the \textit{in situ} monitoring of ICMEs at Venus orbit combined
with empirical and/or propagation models may provide early predictions of Earth-bound CMEs. As PSP is measuring the regions where the solar wind gets accelerated, it is important to study fast solar wind flow from coronal holes and its impacts on the CMEs evolution. SO progressively inclined orbit over the ecliptic will provide new insight onto the polar regions of the Sun and is expected to improve our understanding of the solar wind from coronal holes in the polar regions. Future studies should focus on verifying and evaluating background solar wind models to improve the inputs for CME propagation models. The studies of CMEs and solar wind evolution will be further augmented by the anticipated launches of the ESA Proba-3 (Shestov et al. 2021) satellites in 2022 and the Polarimeter to UNify the Corona and heliosphere (PUNCH) (DeForest et al. 2020) in 2023. The observations from such upcoming missions will be highly complementary to both WISPR onboard PSP and SoloHI onboard SO.

In light of the discussions made above, it is clear that little progress has been made in accurately estimating the arrival time, arrival speed, size, mass, magnetic field configuration and field strength of a particular CME at a location in the heliosphere. This is because various observational and modeling limitations partially prevent a more accurate determination of the CME arrival time. Also, our limited understanding of the physics of solar wind in the inner heliosphere and the immense size of the physical system we are dealing with, further prevent accuracy in the current trends of research (Harrison et al. 2017). There has been good progress in understanding the dynamics of CMEs under the influence of high speed from coronal holes, other CMEs and the ambient pre-conditioned medium, but yet we are far from the complete understanding (Manchester et al. 2017). We note that the energy budget of CMEs has only been studied for a handful of cases within a few solar radii from the Sun. Also, we do not have a good understanding of the shape, size and structure of CME’s front and shock, which also poses challenges for estimating the accurate arrival time of CMEs. It is still difficult to reliably track the evolution of different CME structures, particularly the magnetic flux rope (MFR). Furthermore, the limited knowledge of the physical parameters in the near corona hinders robust modeling of the initial stages of CME propagation and shock evolution. From the space weather perspective, the magnetic properties of the CMEs are often not reliably estimated near the Sun. Also, the heliospheric evolution of the CME magnetic structure (rotation, compression and deflection) and the erosion of the magnetic field due to reconnection with ambient solar wind magnetic fields pose considerable difficulty in predicting both the magnitude and geometry of the CME magnetic field at 1 AU (Wang et al. 2018). Although there have been considerable developments in heliospheric imaging, it has remained extremely difficult to predict the duration of CMEs impacts and their momentum at the Earth.

Despite several limitations to HIs, it seems that there is no better substitute for imaging the vast and crucial distance gap between the Sun and the Earth. This is because it is unlikely that MHD modeling would realistically predict the conditions of the ambient medium for estimating the complex evolution of the CMEs. Therefore, monitoring the CMEs during their continuous journey from the Sun to the Earth has the potential to reveal the physics of evolution of the CMEs. In the future, we expect that a stationary spacecraft outside the Sun–Earth line (e.g., a space weather mission to the L5 point of the Sun–Earth system is being developed by ESA to be launched in 2027), continuously imaging the heliosphere from a stable platform, can overcome some of the limitations suffered by the STEREO. The spacecraft at L4/L5 Lagrange points giving necessary side views of the Sun will observe Earth-directed CMEs with low projection effects. Such spacecraft providing real-time telemetry of good quality data can play a crucial role in achieving a credible space weather prediction. Also, the proposed polar missions, Solaris Solar Polar Mission, if approved, would provide unprecedented observations to improve the understanding of magnetic field connectivity and coupling processes between open and closed magnetic field structures in the heliosphere. At present, the valuable heliospheric observations from recent missions are waiting to be explored extensively. The analysis of these unprecedented observations has the potential to improve our understanding of CME propagation and the performance of space weather prediction tools and models.

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