Pursuing Forecasts of the Behavior and Arrival of Coronal Mass Ejections through Modeling and Observations

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Abstract. Sophisticated instrumentation dedicated to studying and monitoring our Sun’s activity has proliferated in the past few decades, together with the increasing demand of specialized space weather forecasts that address the needs of commercial and government systems. As a result, theoretical and empirical models and techniques of increasing complexity have been developed, aimed at forecasting the occurrence of solar disturbances, their evolution, and time of arrival to Earth. Here we will review groundbreaking and recent methods to predict the propagation and evolution of coronal mass ejections and their driven shocks. The methods rely on a wealth of data sets provided by ground- and space-based observatories, involving remote-sensing observations of the corona and the heliosphere, as well as detections of radio waves.

Keywords. Sun: coronal mass ejections (CMEs), solar-terrestrial relations, interplanetary medium

1. Introduction

The first hints of Sun-Earth connection were revealed in the mid-eighteenth century, as Olof Hiorter and Anders Celsius noticed perturbations in a geomagnetic needle in connection with aurorae. A century later, these magnetic disturbances were found to have the same frequency and phase as sunspots (Sabine 1852). Although several groundbreaking discoveries related with solar physics and solar-terrestrial relations followed in the years to come (\textit{e.g.} Carrington 1859, Hale 1908, Fairfield & Cahill 1966), it was not until the beginning of the space age when coronal mass ejections (CMEs) were discovered. Their existence had been proposed to explain geomagnetic disturbances (see summary in Burlaga \textit{et al.} 1991), so that CMEs were soon associated with magnetic interplanetary structures originating at the Sun (\textit{e.g.} Schwenn 1983, Sheeley \textit{et al.} 1985).

Ground- and space-based observatories dedicated to Heliophysics proliferated in the following years, enabling in-depth studies of the Sun’s interior and atmosphere, as well as of its impact in the interplanetary medium, Earth, and other planets. Several aspects of CMEs came to light, regarding \textit{e.g.} their source regions, kinematics, and morphology. In spite of significant progress on these matters, to date it has not been possible to foresee when and where on the Sun the next CME might take place. This limitation implies that forecasting must be based \textit{sine qua non} with the occurrence of a CME, \textit{i.e.} only once a CME has erupted, its arrival at Earth and degree of influence may be forecasted. The identification of Earth-directed CMEs has proven to be non-trivial, since it is mainly based on observations from white-light coronagraphs. Because of the Thomson scattering effect (\textit{e.g.} Vourlidas & Howard 2006), Earth-directed CMEs may be at times undetected by coronagraphs located in the Sun-Earth line. This problem was addressed by Cremades \textit{et al.} (2015a), who investigated the production of CMEs from an active region crossing
central meridian, and found twice as many CMEs traveling towards Earth when using coronagraphs located \( \sim 90^\circ \) away from the Sun-Earth line, implying a significant number of missed alarms. In addition, a subset of events dubbed “stealth CMEs” (Robbrecht et al. 2009) may not leave perceptible imprints on low coronal images, complicating even more the identification of potentially geoeffective CMEs.

Once a CME is detected, a good assessment of the three-dimensional (3D) trajectory and size serves to determine if it will arrive at Earth, while knowledge on its propagation profile is crucial to ascertain when it will arrive. Furthermore, information on how the associated magnetic fields are configured is key to determine whether the Earth’s magnetosphere is to be disrupted and to what extent. In the next sections, I will briefly discuss tools and models that have been proposed to address these aspects.

2. Determining propagation direction and size

Soon after the discovery of CMEs, there was some speculation on whether CMEs could be best described as planar loops (Trottet & MacQueen 1980) or 3D structures (e.g. Howard et al. 1982, Crifo et al. 1983), with the latter being quickly accepted. Likewise, it did not take long to recognize that CMEs and their trajectories appear projected in the plane of the sky, thus hindering proper assessment of their 3D characteristics. This is particularly critical for events that propagate close to the Sun-Earth line, which are certainly the most threatening for the space weather at Earth. To overcome the problem for these events, particularly halo CMEs, cone models based on coronagraph observations were proposed before (e.g. Howard et al. 1982) and during the SOHO era beginning in the mid-1990s (SOHO: Solar and Heliospheric Observatory; Domingo et al. 1995). Some of these include Zhao et al. (2002), Michalek et al. (2003), Xie et al. (2004), Cremades & Bothmer (2005), Zhao (2008), and Na et al. (2013). The outcome of these models in terms of propagation direction and size is particularly useful to feed models of propagation and arrival time of CMEs and shocks (see Section 4).

Other ways of finding out the 3D propagation direction based on single-viewpoint observations rely on characteristics of the low-coronal environment at the time of eruption. This is the case of the methods proposed by Cremades et al. (2006) and Gopalswamy et al. (2009), which consider coronal holes as playing a key role in the deflection of CMEs from their source regions. Kay et al. (2013) developed a more sophisticated data-driven model of the coronal background that also takes into account CME properties to predict deflection for the first solar radii of propagation.

The launch of the STEREO mission in 2006 (Solar-Terrestrial Relations Observatory; Kaiser et al. 2008) enabled new ways of finding these CME attributes while minimizing uncertainties. The most widespread methods are either based on the tie-pointing/triangulation reconstruction (e.g. Temmer et al. 2009, Mierla et al. 2009, Srivastava et al. 2009, Liu et al. 2009, Liewer et al. 2011), polarization ratio (e.g. Moran et al. 2010, deKoning & Pizzo 2010) or forward modeling (e.g. Thernisien et al. 2009, Wood et al. 2010). The first method requires at least two viewpoints, and that the same parcel of coronal material can be discerned in stereoscopic images, which is not always straightforward. With the polarization ratio technique, however, observations from one viewpoint are enough, although multiple views are helpful to constrain the problem. Forward modeling approaches fit an ad hoc 3D density distribution to achieve visual agreement with data. Best results are obtained when applied to observations from three different viewpoints, while solutions are strongly undetermined for single vantage point observations. Unfortunately, these tools are often unappropriately used, because their limitations are overlooked and an untrained
eye may find various erroneous solutions that fit the same CME. For a comparison of
these and other reconstruction techniques, see Mierla et al. (2009, 2010).

The interpretation of white-light images for size assessment must be taken with care,
given that the outermost rim of a CME may represent the shock (Vourlidas et al. 2013),
especially for the case of CMEs seen as halos. It should be noted that events that succeed
to be seen as halo CMEs in past and present coronagraphs are indeed “special” (Lara et al. 2006),
faster and wider than average (e.g. Shen et al. 2013). In fact, full limb halo CMEs –halo CMEs completely surrounding a coronagraph’s occulter but at the same
time originating close to the solar limb– may be geoeffective (Gopalswamy et al. 2007,
Cid et al. 2012), while a fairly bright and wide CME seen at the limb may not show up
as a halo when changing vantage point by ~90° (Cremades et al. 2015a).

3. Determining flux rope orientation

A period of negative Bz component of the interplanetary magnetic field at 1 AU is well
known for disrupting the Earth’s magnetic field. This can be provided by parts of the
helical magnetic flux rope(s) embedded within interplanetary CMEs (ICMEs) or by the
interplanetary magnetic field compressed ahead of the ICME. While the latter is more
difficult to predict, requiring complex high-resolution dynamic 3D models of the ambient
solar wind, potential geoeffectiveness of a white-light CME may be partially ascertained
based on the knowledge of the configuration of its magnetic flux rope (see Vourlidas et al.
2013 for a discussion on the fraction of CMEs embedding flux ropes).

Bothmer & Schwenn (1998) recognized different magnetic field configuration patterns
in Helios 1 and 2 in-situ data sets, in agreement with the helical magnetic flux rope
picture. The magnetic configuration of filaments could be related to that of the so-called
magnetic clouds detected in-situ, having four possible types, resulting from two possible
directions of the field axis and two possible values of magnetic helicity or handedness.
Although for the examined time interval they found that the axes of the flux ropes
were generally close to the ecliptic plane, later studies identified other orientations (e.g.
between the magnetic configuration of interplanetary flux ropes and that of their solar
sources (e.g. Yurchyshyn 2008, Marubashi et al. 2015) has motivated a number of studies
toward magnetic field prediction at 1 AU (Savani et al. 2015, 2017, Kay et al. 2017).

As stated above, CME deflection from their solar sources and rotation of their main
axis are common effects in the first stages of eruption. While various approaches have
been proposed to tackle the issue of deflection (see Section 2), only few studies address
rotation (e.g. Vourlidas et al. 2011, Kay & Opher 2015, Kay et al. 2017). Instead of
deducing CME rotation with respect to their source regions, at times it can be more
convenient to determine flux rope orientation from white-light observations of CMEs,
given that at heights of a few solar radii they have experienced most of these effects to
eventually behave self-similarly. However, this is not an easy task, since orientations of
the main axis of reconstructed CMEs have large uncertainties (Thernisien et al. 2009),
which in turn may have large impact on the predictions of in-situ conditions through
simulations of ICMEs (e.g. Savani et al. 2017, Kay et al. 2017). Stronger constraints on
latitude, longitude, and tilt of the main axis of white-light CMEs can be achieved with
a proper combination of vantage points and CME propagation direction. As shown by
Cremades and Bothmer (2004), the projected morphology exhibited by CMEs depends on
their propagation direction and orientation with respect to the vantage point (Figure 1a).
If all remote-observing spacecraft as well as the CME trajectory approximately lie in the
same plane, i.e. the ecliptic, to find the orientation of the CME’s main axis will involve
4. Determining time of arrival

Most of the forecasting models naturally focus on the forecasting of arrival times of CMEs and/or their associated shocks, provided that a CME with a propagation direction component toward Earth has been ejected. Inspired by the classification proposed by Zhao & Dryer (2014), forecasting models are here sorted into three classes: (i) empirical, data assimilative models, (ii) physics-based models, and (iii) magnetohydrodynamic (MHD) models. Empirical, data assimilative models rely on typically simple analytic expressions fed with parameters obtained from solar, coronal, or interplanetary detections. Examples of these are those by Gopalswamy et al. (2001, 2005), Wang et al. (2002), Srivastava & Venkatakrishnan (2004), Xie et al. (2006), and Michalek et al. (2008). Other approaches rely on the concept of radial and expansion speed of CMEs (Schwenn et al. 2005, Mäkelä et al. 2016). Prediction techniques may for instance also profit from interplanetary scintillation information (e.g. Jackson et al. 1998, Manoharan 2006), from heliospheric imaging (e.g. Sheeley et al. 2008, Rouillard et al. 2008, Davis et al. 2011, Colaninno et al. 2013, Möstl et al. 2014, Rollett et al. 2016), or from tomographic
considerations (e.g. Jackson et al. 2011). Low-frequency type II radio emissions can be useful to forecast CME shock arrival times, assuming that the emission takes place at the Earth-directed shock sector and that at those distances (farther than 30 solar radii) the shock propagates with nearly constant speed. Only one third of L1 shocks are associated to low-frequency type II events, however shock arrival times based on these emissions have errors of less than $\pm 6$ h for 85% of the events (Cremades et al. 2015b).

Among the physics-based models the Shock Time of Arrival (STOA; Dryer & Smart 1984), the Interplanetary Shock Propagation Model (Smith & Dryer 1990), and the Hakamada-Akasofu-Fry (HAF) version 2 (Fry et al. 2003) stand out. Improvements to the STOA model have been proposed by Qin et al. (2009) and Liu & Qin (2012) on the basis of solar energetic particles and X-rays. The drag-based model assumes that the dominant force exerted on ICMEs is the magnetohydrodynamical equivalent of the aerodynamic drag (Vršnak et al. 2007, 2013). The aforementioned models have errors in time of arrival that range from $\sim 6$ to 12 h. Shi et al. (2015) and Hess & Zhang (2015) have proposed a combination of stereoscopic measurements with the drag-based model, to achieve average errors of 8.6 h for 16 events, and under 3.5 h for seven events respectively. The Shock Propagation Model version 3 by Zhao & Feng (2015) was applied to over 200 Earth-directed events to yield an average absolute error of $\sim 9$h.

Several of the most renowned MHD models are routinely used for space weather prediction purposes. Enlil may be constrained by the Wang-Sheeley-Arge (WSA) method and/or a cone model (Odstrcil et al. 2004, 2005, Xie et al. 2013). CORHEL uses a coronal model (Magnetohydrodynamics outside A Sphere–MAS or WSA) combined with a heliospheric model (MAS or Enlil) (Linker et al. 2009). The Alfven-Wave driven solar wind Model (AWSoM), part of the Space Weather Modeling Framework, is based on the BATS-R-US code (Tóth et al. 2005, 2012, Van der Holst et al. 2014) and can be used in combination with the Eruptive Event Generator – Gibson and Low (Jin et al. 2017). The HAF version 3 combined with the 3D MHD model by Wu et al. (2007, 2011), and the Solar-InterPlanetary Conservation Element/Solution Element MHD model by Feng et al. (2007, 2010) are other prediction models of widespread use.

The inherent uncertainties of input parameters, the limited knowledge on how kinematics and morphology behave for different events, and the difficulties in determining the real solar wind conditions in 3D space and time are the main factors that affect the performance of existing models (Zhao & Dryer 2014). This includes interactions between transients and with other structures (e.g. Dasso et al. 2009, Liu et al. 2012, Lugaz et al. 2013, Temmer et al. 2014). According to Burlaga (2002), two out of three ICMEs are complex events, which implies that realistic simulations require a high level of complexity.

5. Final remarks

In the past three decades, diversity and progress of Heliophysics-dedicated space missions and ground-based observatories have enabled enormous advancement and increasing complexity of techniques and models aimed at forecasting CME behavior and arrival. However, the various techniques and models have different caveats, pros and cons, e.g. with respect to simplicity, running time, lead time, data assimilation, and number of events on which they have been validated. At the present time, the maximum benefit can only be achieved by recognizing which methods or models perform best under different circumstances, not only to avoid false and missed alarms, but also to obtain good proxies of arrival time. Furthermore, coronagraphs and EUV imagers, particularly those offset from the Sun-Earth line, are compelling to identify Earth-directed events and forecast their time of arrival.
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References

Bothmer, V. & Schwenn, R. 1998, Annales Geophysicae, 16, 1
Burlaga, L. F. E. 1991, Physics and Chemistry in Space, 21, 1