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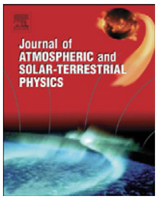

Editorial

On three-dimensional aspects of CMEs, their source regions and interplanetary manifestations: Introduction to special issue

1. Introduction

Coronal mass ejections (CMEs) are transient events where coronal plasma and magnetic fields are ejected from the Sun at velocities ranging from less than 200 km s^{-1} to more than 2000 km s^{-1}. CMEs observed while propagating into the interplanetary space are called interplanetary CMEs or ICMEs. These phenomena play an important role for space weather, as they can induce severe geomagnetic storms when they interact with the Earth's magnetosphere.

Until the launch of Solar TErrestrial RElations Observatory (STEREO) in October 2006, the estimation of the 3D configuration of coronal mass ejections was possible, only by indirect methods, viz. from MHD models or by using 2D images of the Sun and making several assumptions about the CME propagation direction and shape. The STEREO mission was conceived in order to overcome the single viewpoint limitation. Because of a dual perspective of the Sun, and the inner-heliosphere, the twin STEREO spacecraft are now providing the needed data in order to help us understand the 3D structure of solar transients. In particular, the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) on STEREO is a suite of remote sensing instruments consisting of an Extreme UltraViolet Imager (EUVI), two white-light coronagraphs COR1 and COR2, and two telescopes that comprise the Heliospheric Imager (HI1 and HI2). The main objective of these SECCHI instruments is to observe CMEs from their birth at the Sun, through the corona and into the heliosphere. A complete instrument suite is being carried on each of the two STEREO spacecraft i.e. Ahead and Behind, which continuously track CMEs from two vantage points as the spacecraft separate from each other at the rate of about 45° per year.

With the new data from STEREO, it is now possible to relax some of these assumptions made when using single images, and get a better understanding of the CME morphology. The purpose of this special issue is to bring together 3D observations and models of CMEs, ICMEs and their source regions on the Sun in order to review the present status of the subject. In this direction, the research contributions in this issue are unique as they not only focus on the previous findings but also present our current understanding in 3D studies of CMEs.

This special issue has been structured in 3 different sections, as described below:

(I) **CMEs source regions: 3D observations and models**
This section includes contributions on 3D reconstruction and/or modeling of active regions, prominences, EIT waves, etc.

(II) **CMEs: 3D observations and models**
The second section deals with CME 3D morphology and therefore includes research articles on forward modeling, 3D simulations and determination of propagation direction of CMEs in three dimensions. Both the pre-STEREO and the STEREO era have been covered.

(III) **Interplanetary CMEs: 3D observations and models**
The last section includes 3D simulations of ICMEs; 3D reconstruction of ICMEs using STEREO and pre-STEREO data and also multi-spacecraft observations of ICMEs.

The objective of this introductory article is to provide an overview of the past efforts, present status, and future perspective of research in the field of 3D reconstruction of CMEs, their sources and their interplanetary counterparts. It also summarizes very briefly, the papers included in the Special Issue. Some of the papers in this issue were presented orally at the European Geophysical Union meeting held in Vienna, Austria in April 2009. The Guest Editors invited presenters to further develop and expand their ideas in the form of review/contributed articles for this Special Issue in JASTP. It was essential owing to the relevance and importance of the new observations of the Sun recorded by STEREO in improving our understanding of 3D structure of CMEs and ICMEs that the high-quality and original presentations made at the EGU be tied together with the common goal of reviewing the current status of the field.

As explained above, one of the main objectives of this Special Issue is to highlight the new observations made by the STEREO spacecraft specifically in the field of 3D studies of CMEs using these data. It also focuses on the new techniques that have been developed for understanding the 3D structure involving stereoscopy, triangulation and forward modeling, among others. The special issue aims at showcasing the recent achievements in this area as compared to the efforts made in the past i.e. in the pre-STEREO era.

In what follows, we present a brief summary of the 17 papers contributed in this Special Issue with a brief overview of the past efforts, current understanding and future perspective of research in the field of 3D reconstructions of CMEs and ICMEs.

1.1. *CMEs source regions: 3D observations and models*

STEREO observations provide an excellent opportunity to understand the large-scale dynamical phenomena of CMEs and their source regions. For example, advances have been achieved in the study of active regions, eruptive prominences, post-eruptive

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arcades, EIT waves and other associated phenomena. 3D reconstruction of coronal loops, prominences and other small-scale structures in the solar atmosphere requires imaging from two vantage points that have an angular separation of less than 15° as shown by Inhester (2006), Feng et al. (2007), Gissot et al. (2008) Aschwanden et al. (2008) and Rodriguez et al. (2009). While on the other hand, a larger angular separation between the two vantage points seems necessary for the 3D reconstruction of large-scale optically thin structures e.g. EIT waves (Aschwanden and Wuelser, this volume).

One of the early achievements of the stereoscopy was the 3D reconstruction of active regions in the solar corona, using stereoscopic image pairs from the STEREO/EUVI instrument (Wuelser et al., 2004a, b), which is part of the SECCHI instruments suite (Howard et al., 2008a, b). Aschwanden and Wuelser in this special issue present a detailed review on this vast subject. This review not only includes the 3D geometry of coronal loops but also their 3D electron density and temperature distribution. This was further applied for the 3D magnetic field reconstruction, as well as the 3D reconstruction of CME-related phenomena, such as EUV dimming, CME acceleration and CME bubble expansion. The authors also point out that 3D reconstruction of structures in the solar corona has been attempted already in the pre-STEREO era, using solar-rotation stereoscopy and tomography (e.g., Berton and Sakurai, 1985; Koutchmy and Molodensky, 1992; Aschwanden and Bastian, 1994; Frazin, 2000), which requires quasi-stationary structures over a period of approximately 7 days and which are difficult to find in the highly dynamic corona, although it proves useful to reconstruct large-scale 3D coronal structures, such as coronal holes and streamers (e.g., Wang et al., 2000; Saez et al., 2007; Zhukov et al., 2008). It can be concluded that the detailed 3D density and temperature structure of an active region can be modeled using the method of instant stereoscopic tomography (using STEREO observations) with orders of magnitude higher spatial resolution than with standard solar-rotation tomography.

The three-dimensional study of other associated phenomena, for example, EIT waves has also been attempted using STEREO observations. An overview of the observed properties of such large-scale wave-like fronts in the solar atmosphere e.g. Moreton waves, EIT waves is presented by Zhukov in the special issue (Zhukov, this volume). The models proposed to explain EIT wave phenomena are reviewed in the light of new key observations made by the STEREO mission. The implications of these observations for EIT wave models, which have significantly advanced our understanding of this phenomenon are discussed. High-cadence EUVI data confirm the possibility of the EIT wave deceleration (Veronig et al., 2008; Long et al., 2008), although constant velocities (Ma et al., 2009) and more complicated speed profiles (Zhukov et al., 2009) have also been observed. The evolution of the wave profile supports the idea of the wave first driven by the CME expanding flanks, which is propagating freely (Veronig et al., 2010). Its reflection at the coronal hole boundary (Long et al., 2008; Gopalswamy et al., 2009) on the other hand, provides strong evidence that the EIT wave is a true wave. Based on several observational studies made so far, the interpretations of the 3D structure of EIT waves and their relation to the associated CME structures are often contradictory, with some authors (Patsourakos et al., 2009; Patsourakos and Vourlidas, 2009; Kienreich et al., 2009) favoring true wave, others (Ma et al., 2009; Yang and Chen, 2010) favoring non-wave and yet others (Cohen et al., 2009) favoring bimodal hypotheses of the EIT wave origin. As per our present understanding, one is easily led to the conclusion that no single model can explain a large variety of the observed EIT wave properties.

Prominence eruptions are probably the most impressive evidence of eruptions in the solar corona. The link between them and CMEs cannot be correctly understood without a clear view on their three-dimensional properties. The review paper by Bemporad (this volume) in this special issue emphasizes the importance of STEREO mission data in the determination of real prominence shapes and trajectories during eruptions in three dimensions. These data give us now a unique capability to identify twisted or ribbon-like structures, helical or planar motions of prominences. These parameters are of fundamental importance for understanding the physical phenomena triggering their eruption and affecting their early evolution. This paper not only describes different stereoscopic techniques used for analyzing STEREO data but also compares the results of these with those that were developed prior to the launch of STEREO. They confirm that 3D kinematics derived from STEREO observations, in fact, are in agreement with those obtained by spectroscopic analysis with a larger number of assumptions. To this end, the author concludes that the STEREO capabilities leading to the study of the 3D configuration of filaments and their eruptions have not been fully exploited so far, due to the fact that not many observations of eruptive phenomena are available for stereoscopic analysis. This, is partly owing to the low activity related to the minimum phase of the solar cycle when the STEREO spacecraft were launched and partly due to the increasing angle of separation of the two spacecraft with time, which complicates the application of stereoscopic techniques to the observations.

As a logical step forward, this special issue on the other hand, includes two research papers which are dedicated to the study of the 3D kinematics of erupting prominences using EUVI stereo observations. The first one is a detailed analysis of the structure of an erupting prominence made by Thompson (this volume), which makes use of the EUVI images taken by STEREO A and B. By applying the tie-pointing technique on these small-scale filamentary features on the STEREO images, the author concludes that the prominence is organized primarily as a vertical sheet of material, which rotates about the radial axis as it erupts by at least 90° and more. Part of this rotation could be attributed due to a rolling of the prominence as it erupts, and partly to morphological changes caused by reconnection.

Another important study in this field has been made and contributed to the special issue by Panasenco et al. (this volume), which highlights the large-scale dynamical motion of three eruptive filaments which reveal evidence of sideways rolling motion beginning at the crest of the erupting filament. These displayed highly non-radial outward motion and occurred adjacent to coronal holes. Out of these, one eruptive prominence was observed by both spacecraft and the observations clearly demonstrate that the non-radial motion is related to global magnetic configuration force imbalances.

In summary, analysis of individual cases of eruptive prominences observed by STEREO have revealed clues of initial forces governing the eruptive phase. These results also call for analysis of more data-sets to understand the relationships found between rolling motion, non-radial motions of associated CMEs, and their proximity to coronal holes, in addition to the filament environment i.e. magnetic fields close to the filament, the filament channel, filament cavity, and the developing field of the CME.

1.2. CMEs: 3D observations and models

As mentioned earlier, CMEs are typically observed in coronagraph white-light images, as large scale, bright features, moving out in the interplanetary space at speeds ranging from less than

200 km s^{-1} to more than 2000 km s^{-1} (e.g. Yurchyshyn et al., 2005). Before the launch of STEREO in October 2006, the CMEs were observed only from one view direction (Earth view) either by coronagraphs on spatial missions like SMM or SOHO, or by ground based coronagraphs. This data provided us a two-dimensional representation of the CME three-dimensional structure projected onto the plane of the sky. From a 2D image, in order to derive the 3D structure of the CME, many assumptions had to be made e.g. pre-defined shapes, self-similar expansion, etc.

The CMEs display different geometric shapes from simple bubble-like shape to more complex structures like flux-ropes. 3D reconstruction can only be attempted considering such simple geometry where an initial parametric description of the 3D distribution of electrons is required, and forward modeling (FM) is performed to generate a set of synthetic images which are compared to the observed ones. Trial and error adjustments of the parameters then produce the best fit characterizing the structure of the CME (e.g. Chen et al., 1997; Thernisien et al., 2006).

With the launch of STEREO, two or three (if one includes SOHO) view directions are now available to make the reconstruction of CMEs, and as a consequence, the assumptions are more relaxed (Mierla et al., 2010). Nevertheless, a complete 3D geometry of CMEs is not possible to be derived from 1, 2 or 3 view directions only. One complication arises also from the fact that the CME plasma is optically thin and its observed radiance results from the integration of the Thomson scattering by coronal electrons along the line of sight (LOS). This may lead to the possibility that overlapping structures will create a sharp bright boundary from one view direction but display a more diffuse complex structure from the other, thus complicating the proper identification of CME boundaries or their fine structure. As a result, the observations have to be combined with MHD modeling in order to have a correct identification of these large-scale structures.

The second part of this volume aims in bringing up-to-date the efforts that have been made in this field (3D CME reconstruction) before and during the STEREO era. A review on different reconstruction techniques of CMEs is given in the paper of Thernisien et al. (this volume). The authors focus on the techniques relevant to the CME morphology: forward modeling, polarimetry, spectroscopy and direct inversion. They also discuss the limitations and considerations involved in each technique.

Liewer et al. (this volume), apply stereoscopic analysis on CMEs in order to derive their direction of propagation. They compare their results with those obtained by Thernisien et al. (2009) using forward modeling, and find good agreement between the two methods. The authors also calculate the systematic errors introduced by the fact that each spacecraft sees a different apparent leading edge.

Mierla et al. (this volume) apply the local correlation and triangulation method on a CME observed on 31 August 2007 in order to derive the longitudinal and latitudinal extent of the CME. They found that the latitudinal size is smaller than the longitudinal size, indicating an elliptical cone like structure or a flux-rope like structure with very little tilt relative to the ecliptic. They also emphasize the need to apply this method on more events to validate this finding.

An up-to-date review on CME modeling is given in the paper by Poedts and Jacobs (this volume). They mainly focus on the attempt to retrieve the initiation and propagation of CMEs in the framework of computational magneto-fluid dynamics. The authors also include a brief overview of current models for the background solar wind as it has been shown that the background solar wind affects the onset and initial evolution of CMEs quite substantially.

1.3. Interplanetary CMEs: 3D observations and models

The three-dimensional configuration of ICMEs is a very challenging topic to address. This is mainly due to the nature of the observations available to probe the global configuration of the transients. Normally, the *in-situ* data used represents a 1D cut through a 3D structure. Therefore, some assumptions need to be made, in order to infer the global configuration of ICMEs.

Probably the simplest way of obtaining information on the general configuration of ICMEs is by fitting flux rope models to the magnetic field inside ICMEs. This has been done in the past by many authors e.g. Burlaga (1988), Lepping et al. (1990), Marubashi (1997), Hidalgo et al. (2002) and Romashets and Vandas (2003). These models can provide information mainly on the orientation of the magnetic field axis, which together with a prescribed geometrical shape can help to get an idea of the overall structure of the ICME. The application of these models is limited to magnetic cloud type ejecta only, as they are the only type of ICMEs which present a magnetic field configuration which can be modeled.

A major step ahead in this direction consists in applying numerical simulations methods. In this special issue, Lugaz and Roussev (this volume) present a review on recent efforts on numerical simulations that help gain a better understanding of the magnetic topology and internal structure of ICMEs, in general. Multi-spacecraft observations of ICMEs provide a very valuable contribution in order to infer the global structure of ICMEs. The work by Kilpua et al. (this volume) provides a good review on this topic. ICMEs can drive shocks which can have large extensions in the heliosphere, even beyond the dimensions of their driver. de Lucas and co-authors present in this volume, an analysis of ICMEs observed by the Helios spacecraft in the inner-heliosphere, in search for the real extension of shocks.

With the launch of STEREO in 2006, numerous new studies on ICME structure have been made. In particular, the new Heliospheric Imagers (HI) instruments (Eyles et al., in press), part of the SECCHI instrument suite (Howard, et al., 2008a, b) are providing novel information on the structure and dynamics of ICMEs in the heliosphere. It is now possible to track an ICME all the way from the Sun to the Earth. The paper by Rouillard (this volume) gives a comprehensive overview of these new results. As a case study, Xiong et al. (this volume) studied the propagation of a shock, not only using HI, but also interplanetary scintillation (IPS) data. Furthermore, the HI data has also been used by Howard (this volume) in order to obtain the 3D configuration of CMEs. Complementary to these observations are the ones provided by SMEI, which are used in Jackson et al. (this volume) paper on 3D heliospheric tomography, in this issue.

The interaction of ICMEs amongst themselves, or with other transients in the heliosphere can influence strongly their 3D structure and magnetic field configuration. Farrugia et al. (this volume) provide a case study of a magnetic cloud interacting with a co-rotating interaction region (CIR).

Future perspective: Although it is well understood that the increasing angle of separation between the two STEREO spacecraft A and B will pose a problem for 3D reconstruction of small-scale features, nevertheless the STEREO spacecraft continue to provide novel and exciting results even when the separation angle is more than 90°. Further, when the spacecraft A and B will be 180° apart they will provide a complete view of the entire Sun, which is extremely important from the perspective of forecasting space weather. During this time, the source regions of CMEs, viz., active regions, filaments, etc. can be observed prior to their appearance on the East limb seen from Earth. Combined with the view from Earth and the STEREO spacecraft, the whole Sun view will also provide important unprecedented information on CMEs and their propagation, thereby providing crucial input for predicting their arrival times at the Earth. The increasing separation angle of STEREO spacecraft during the maximum of solar activity cycle will allow observations of increased number of CMEs and therefore will be helpful to compare the 3D structure of CMEs observed during solar minimum and maximum phase.

This time will also be an exciting time for the 3D studies on ICMEs and magnetic clouds, as important information will be provided by STEREO together with ACE and Wind enabling multipoint sampling of an ICME ejecta. This will also help in constraining the propagation models of CMEs.

An important aspect of 3D studies, expected in future with STEREO is based on quadrature perspective of CMEs and ICMEs. The only opportunity available in the past for such quadrature observations was with Helios and Solwind spacecraft missions. The quadrature observations available by combining STEREO A and B with either of SOHO, ACE or Wind is expected to improve our understanding of CME propagation, in particular on the role of acceleration/deceleration during propagation in the interplanetary medium.

In summary, owing to its increasing angle of separation, STEREO will continue to provide unprecedented 3D view of CMEs and ICMEs thus improving our understanding of their sources and propagation in the interplanetary medium and provide inputs for better forecasting of space weather.

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