

Three-dimensional reconstruction of coronal mass ejections using heliospheric imager data

Timothy A. Howard*

Department of Space Studies, Southwest Research Institute, 1050 Walnut St, Boulder, CO 80302, USA

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ABSTRACT

Innovative techniques have been developed to extract three-dimensional (3-D) information on coronal mass ejections. Some techniques have only been available since the launch of the STEREO spacecraft, where geometry can be applied to white light observations from three different viewpoints. Another technique not necessarily requiring the multiple-viewpoint capabilities of STEREO involves heliospheric imaging. With heliospheric imagers, we may take advantage of the breakdown in geometrical and Thomson scattering linearity and, with careful analysis of the data, extract 3-D parameters from CME images. In this review we discuss the various techniques that are being developed and used to reconstruct the 3-D structure and kinematic evolution of CMEs, with a particular emphasis on the work of the author and colleagues. Following a brief review of multiple-viewpoint coronagraph analysis, we focus on techniques involving heliospheric images, which can be used to achieve the reconstruction with a good degree of accuracy without the need for auxiliary data.

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1. Introduction

Coronal mass ejections (CMEs) are large eruptions of plasma and magnetic field from the Sun. They may contain masses in excess of 10^{13} kg and early in their evolution they can achieve speeds in excess of 3000 km/s. CMEs are believed to be responsible for the removal of large quantities of magnetic energy and plasma from the solar atmosphere (Low, 1996), and a single CME contains more energy than all of the other solar eruptive phenomena (e.g. flares, solar energetic particles) combined (Emslie et al., 2004). They are hence an important mechanism in solar cycle evolution. Upon their occasional impact with the Earth they compress the magnetosphere and may inject large quantities of energetic particles resulting in large disturbances known as (geo)magnetic storms (e.g. Dungey, 1961, 1963). Magnetic storms are responsible for a variety of damage to technological infrastructure on and near the Earth, including power station damage, communications disruption, spacecraft damage and destruction and increased radiation dosage to aircraft passengers and astronauts. The NRC report by Baker et al. (2009) provides a review of the status quo regarding space weather. Improving our understanding of CMEs is hence of great significance to both scientific and technological objectives.

CMEs are very faint relative to the brightness of the Sun, and so they have traditionally been observed using white light coronagraphs that block out the photospheric light using an occulting disk, revealing the faint surrounding corona. These coronagraphs detect the Thomson scattered light off free electrons in the CME, and the most successful coronagraphs for CME detection have all been on spacecraft. This includes those on board OSO-7 (Tousey, 1973) and Skylab (Gosling et al., 1974), the later Solwind (Michels et al., 1980) and C/P on board SMM (MacQueen et al., 1980), and the more recent LASCO on SOHO (Brueckner et al., 1995) and the CORs on STEREO (Howard et al., 2008). Statistical studies on CMEs have been reported by many workers, including Hundhausen et al. (1994), St. Cyr et al. (2000), and Yashiro et al. (2004).

1.1. Kinematic measurements of CMEs

From the early days of CME observations, measurements of height, speed and acceleration were obtained by measuring the location of the leading edge of the structure in the coronagraph relative to the center of the Sun. They provide a reasonable approximation of the location of the CME as it moves through the field of view of the coronagraph but are limited due to the physics by which the CME is observed in white light. Firstly the images are sky plane projections, and so measurements of distance do not represent the actual three-dimensional (3-D) distance of the structure, but rather this distance projected into the sky plane. That is,

$$d_{\text{measured}} = d_{\text{actual}} \cos \theta, \quad (1)$$

* Tel.: +1 720 240 0140; fax: +1 303 546 9687.

E-mail address: howard@boulder.swri.edu

URL: <http://www.boulder.swri.edu/~howard/>

where θ is the angle the central axis of the CME makes with the sky plane.

The other limitation of white light images is due to the Thomson scattering physics that enable us to detect them. These bias CME intensities to near the plane of the sky because at small angles from the Sun the scattered light is maximized (e.g. Andrews et al., 1998). Combining geometry and the scattering physics we may convert the angular separation into a physical distance by applying some simple, yet unavoidable approximations. These allow a simplified conversion to distance units but at the cost of removing 3-D information about the CME from the coronagraph images. Further from the Sun this linearity breaks down which increases the complexity of the required analysis, but enables the extraction of 3-D information.

This review discusses recent developments in the extraction of 3-D information on CMEs using coronagraph and heliospheric imager data alone. Such developments represent a great advance in the study of CMEs as the reliance on auxiliary data to identify 3-D information has led to misunderstanding and misinterpretation of CME data. We discuss the various techniques that are being developed and used to reconstruct the 3-D structure and kinematic evolution of CMEs, with a particular emphasis on the work of the author and colleagues. We begin with a brief review of techniques used to identify 3-D information about CMEs followed by a discussion of the utility of the stereoscopic capabilities of the STEREO coronagraphs to attempt 3-D reconstruction. We then move on to a discussion of heliospheric imagers and how they may be used to identify 3-D CME parameters by taking advantage of the breakdown of the linearity that occurs when CMEs are far from the Sun. We demonstrate that heliospheric image data alone may be utilized for fast, reliable and potentially accurate 3-D CME reconstruction without the need for auxiliary data or a stereoscopic viewpoint, and conclude that a replacement next generation heliospheric imager is urgently needed before the current imagers lose their capability for space weather forecasting.

2. Extracting three-dimensional information from coronagraphs

Workers in the past have attempted to identify 3-D properties of coronagraph CMEs using auxiliary data (i.e. solar “surface” features) as indicators. Such indicators take many forms, including active regions (e.g. Falconer et al., 2002), X-ray and H α flares (e.g. Howard et al., 2008), disappearing filaments (erupting

prominences) (e.g. Li and Luhmann, 2006) and post-eruptive arcades (Tripathi et al., 2004). These indicators are often labeled as the source or origin of the CME (e.g. Owens and Cargill, 2004; Gopalswamy, 2004, 2009; Wang et al., 2006; Gopalswamy et al., 2007), although this is incorrect. Solar flares, for example, have long been known to be associated with CMEs at only the secondary or tertiary level (Kahler, 1992; Gosling, 1993), with the timing of the flare not coincident with the onset of the CME (Harrison et al., 1985) and the location of the flare associated with just a single footpoint of the CME (Simnett and Harrison, 1984). Solar surface indicators are also limited because they do not provide information on changes to the CME during its evolution through the heliosphere (e.g. change of direction). Hence, the extraction of 3-D CME information using solar surface indicators have been met with limited success.

STEREO coronagraph data have for the first time provided a means to identify 3-D information from coronagraph data alone. This is because of the angular separation between both STEREO spacecraft and the Sun–Earth line, enabling the geometrical perspective to be recognized. When observed with coronagraphs, the CME is close enough to the Sun to enable the safe assumption that geometrical features commonly observed from different viewpoints are at the same location in 3-D space. Relative differences in the apparent structure of the CME can then be assumed to be entirely due to projection effects. Hence, by measuring the relative location of a number of common features observed on the CME from the CORs and LASCO we may apply simple geometrical triangulation to identify the 3-D location of each feature. Such a technique was performed by Howard and Tappin (2008) who identified the 3-D location of two CMEs observed by LASCO and the CORs in November 2007. Fig. 1 shows their Fig. 2c, showing the effects of projection on the same CME observed from two viewpoints. The CME in the COR2-A image on the left is narrower and further from the Sun than the CME in the COR2-B image on the right even though both images were obtained at the same time. This is because the location of this CME is closer to the plane of the sky of STEREO-A than STEREO-B.

Fig. 2 shows the location of both CMEs on the solar surface and in the ecliptic plane as determined by Howard and Tappin (2008) (their Fig. 5). The three traces on each solar image indicate the locations relative to LASCO (L) and COR2-A and B (A and B) at three locations, the northern and southern flanks, and the central point. The largest deviation between the three instruments was at the northern flank because there is a greater relative uncertainty when the measured point is closest to the same plane as the observers. The difference in longitude of the two events between

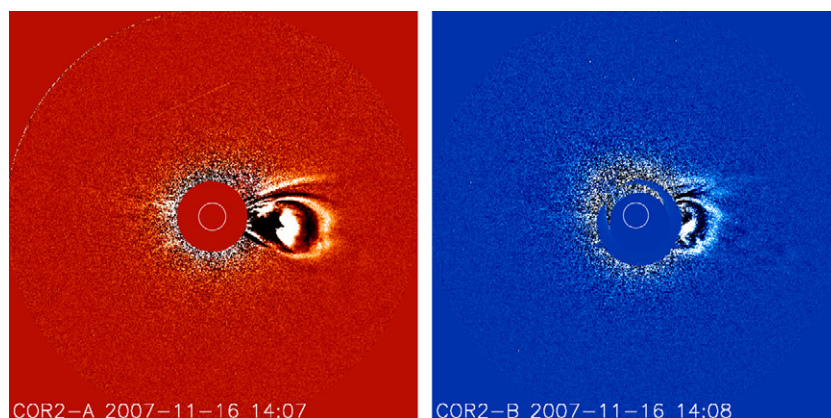


Fig. 1. Two STEREO/COR2 coronagraph images of a single CME obtained from two different viewpoints. Both images were taken on November 16, 2007 at 14:07 UT. At the time of these images, both STEREO were approximately 20° from the Sun–Earth line (and therefore 40° from each other), with STEREO-A (COR2-A, left) ahead and STEREO-B (COR2-B, right) behind. The solid disk in the center is the occulting disk and the white circle in both images represents the solar disk (Howard and Tappin, 2008).

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