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3-D views of the expanding CME: from the Sun to 1AU

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Abstract. Three-dimensional information on Coronal Mass Ejections (CMEs) can be obtained from a wide range of in-situ measurements and remote-sensing techniques. Extreme ultraviolet (EUV) and white-light imaging sensed from several vantage points can be used to infer the 3-D geometry of the different parts that constitute a CME. High-resolution and high-cadence coronal imaging provides detailed information on the formation and release phase of a magnetic flux rope, the lateral expansion of the CME and the reconfiguration of the corona associated with the effects of pressure variations and reconnection. The evolution of the CME in the interplanetary medium and the connection of its various substructures with in-situ measurements can be obtained from multi-point heliospheric imaging.

Keywords. Solar Wind, Solar Activity, Coronal Mass Ejections, Corotating Interaction Regions

1. Introduction

We discuss recent observations, made by the Solar-Terrestrial Relations Observatory (STEREO) and the Solar Dynamics Observatory (SDO), of the formation, interaction and propagation of CMEs from the Sun to 1AU. We divide the CME structure into several parts: the prominence, the cavity and the bright fronts as envisioned by Illing and Hundhausen (1985). Only a small fraction of CMEs have these clearly distinct parts, at most 30% of all events (see e.g. Munro *et al.* 1979), however it provides a convenient framework to discuss in general terms the release and propagation of a CME. Recent results have provided new clues on the nature of cavities and bright fronts, leading to the concept of the five-part structure CME (Vourlidas *et al.* 2012).

2. Dark cavity

The formation and release of a CME can take from several minutes to several days. ProtoCMEs can be observed as cavities in the million-degree corona. When these cavities remain in suspension for several hours, high-cadence EUV imaging reveals that material spins inside them (e.g. Gibson *et al.* 2010). This spinning material likely streams along helical magnetic fields embedded inside these cavities (e.g. Wang and Stenborg 2010). Lower temperature plasma at temperatures near 50kK, called prominence material, is commonly observed at the bottom of this cavity (Berger *et al.* 2012). This prominence material is not always static but the observed motions remain spatially confined to the bottom (sunward edge) of the cavity (Gibson *et al.* 2006). The presence of prominence material is expected since cavities are always situated below helmet streamers, right above polarity inversion lines determined by photospheric magnetograms. During fast and impulsive CME events cavities appear and disappear from the EUV corona within minutes. SDO images permit unprecedented measurements of the lateral and radial expansions of cavities in the lower corona during these few minutes (Patsourakos *et al.* 2010a, Cheng *et al.* 2012). They show that cavities can undergo an intial phase of strong over-expansion (Patsourakos *et al.* 2010b) with measured expansion speeds in excess of 700 km s^{-1} (Cheng *et al.* 2012; Rouillard *et al.* 2013). These sudden cavity expansions tend to originate in strong magnetic field regions, likely some distance from the center of the peak magnetic distribution of active regions (Wang and Zhang 2007). Indeed, the presence of too strong confinement magnetic fields is thought to prevent cavity expansions/eruptions and the subsequent manifestation of a CME (e.g. Török and Kliem 2005). For events that do erupt, the question of whether the flux rope is formed during the eruption, or whether the flux rope existed prior to the eruption, remains controversial.

The extension of the cavity in white-light images (e.g. coronagraphs) is a dark circular or elliptical (depending on the viewing angle) region located within the larger CME (Thernisien *et al.* 2009). 3-D reconstructions of the white light scattered by electrons located on the surface of hollow and therefore dark cavities show that the latter are in fact the cross section of a three-dimensional croissant-shaped structure (Chen *et al.* 1997, Thernisien *et al.* 2009, 2011). It had long been suggested that dark cavities in white-light images are the location of the twisted magnetic field that forms the flux rope (e.g. Chen *et al.* 1997). Continuous tracking of the dark cavities of gradual CMEs to 1AU, using STEREO images, has confirmed that the in-situ signature of a cavity passing over a measuring spacecraft is a rotation of the magnetic vector that can be interpreted as a magnetic flux rope (Rouillard *et al.* 2009, Möstl *et al.* 2009). For well-defined and simple CME events, the 3-D orientation of the croissant reconstructed from white-light images is in good agreement with that of the magnetic flux rope inferred from in-situ measurements (Rouillard *et al.* 2009, Wood *et al.* 2010). These slow cavities retained their circular cross-section as they propagated to 1AU, suggesting a self-similar 3-D expansion of the magnetic flux rope during its propagation to 1AU (Rouillard *et al.* 2009, Wood *et al.* 2010). For some very gradual and slow CMEs, cavities are either absent in EUV or poorly defined in white-light images. The emergence over several days of distinct loops is instead observed in white-light images until the sudden catastrophic anti-sunward release of the back-end of the CME (Sheeley and Wang 2007, Wood *et al.* 2012). This catastrophic release is often associated with loops collapsing back towards the Sun in the phenomenon known as in-out pairs (Sheeley and Wang 2007).

3. The bright fronts

STEREO imaging, during quadrature orbital configuration in 2009, has demonstrated that the so-called Extreme-Ultraviolet (EUV) waves are clearest during the lateral expansion of the cavity. They originate near the strong pressure gradients generated on the flanks of these cavities (Patsourakos and Vourlidas 2009). The strong lateral expansion phase has generally ceased by the time a CME reaches 2 Rs, the EUV wave is then no longer confined to the edges of the cavity and becomes more freely propagating. Further deflections of ambient coronal material are observed simultaneously in white-light images, together with the release over a wide longitude band of solar energetic particle events (Rouillard *et al.* 2012). Two layers, of often different brightness intensities, are observed in outer coronagraphs and in numerical simulations. These layers appear to surround the dark cavity (Ontiveros and Vourlidas 2009; Rouillard *et al.* 2012). The inner layer corresponds to the plasma accumulated directly on the surface of the cavity (likely with the lifted overlying fields), termed N-shell or plasma pile-up (e.g. Hundhausen 1972). While the dark cavity is the likely location of the core field of the CME, originating from the vicinity of a neutral line, the regions surrounding the cavity, in particular its antisunward edge, must at first contain large-scale overlying (or else background) magnetic fields (Riley *et al.* 2008). In contrast to the inner layer that remains confined to the edges of the CME cavity, the fainter outer layer can engulf the entire Sun (Rouillard *et al.* 2013). Numerical simulations suggest that the anti-sunward boundary of this outer layer can mark the location of the coronal shock when its speed exceeds the local ambient characteristic speed (Vourlidas *et al.* 2012). For the very fast 2012 July 23 event multi-point observations clearly showed that the fastest section of the outer layer is directly ahead of the CME (>3000 kms^{-1}) where a shock is continuously driven (Rouillard *et al.* 2013). As the CME progresses in the outer corona, multi-point (heliospheric) images show that the different layers become a single bright leading front that can take the shape of a bow wave (Wood *et al.* 2011, Rouillard *et al.* 2011). The in-situ signature of this bow wave is, as expected, the location of an interplanetary shock (Rouillard *et al.* 2011).

4. Conclusion

Significant progress has been made concerning the nature and evolution of the dark cavity and its surrounding brightness variations. Additional progress remains to be done with regards to the nature and in-situ properties of post-cavity material by tracking prominences or post-CME current sheets continuously to 1AU and studying the composition of this material (e.g. Lepri and Zurbuchen 2010).

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