

RELATIONSHIP BETWEEN EARTH-DIRECTED SOLAR ERUPTIONS AND MAGNETIC CLOUDS AT 1AU: A BRIEF REVIEW

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We review relationships between coronal mass ejections (CMEs), EIT post eruption arcades, and the coronal neutral line associated with global magnetic field and magnetic clouds near the Earth. Our previous findings indicate that the orientation of a halo CME elongation may correspond to the orientation of the underlying flux rope. Here we revisit these preliminary reports by comparing orientation angles of elongated LASCO CMEs, both full and partial halos, to the post eruption arcades. Based on 100 analysed events, it was found that the overwhelming majority of halo CMEs are elongated in the direction of the axial field of the post eruption arcades. Moreover, this conclusion also holds for partial halo CMEs as well as for events that originate further from the disk center. This suggests that the projection effect does not drastically change the appearance of full and partial halos and their images still bear reliable information about the underlying magnetic fields. We also compared orientations of the erupted fields near the Sun and in the interplanetary space and found that the local tilt of the coronal neutral line at 2.5 solar radii is well correlated with the magnetic cloud axis measured near the Earth. We suggest that the heliospheric magnetic fields significantly affect the propagating ejecta. Sometimes, the ejecta may even rotate so that its axis locally aligns itself with the heliospheric current sheet.

1. Introduction

Geomagnetic storms are major disturbances in the Earth's magnetosphere that occur when the interplanetary magnetic field turns southward and remains so for a prolonged period of time [1, 2, 3]. Reconnection between the southward-directed (relative to the ecliptic plane) component of the solar wind-carried magnetic field, B_z , and the northward-directed geomagnetic field can occur at the dayside magnetopause, resulting in the transfer of significant amounts of energy from the solar wind into the Earth's magnetosphere. During a typical storm, an enhanced ring current is created and the auroral electrojets in both hemispheres move (often dramatically) equatorward. This is evidenced by a decrease in the geomagnetic field at near-equatorial magnetic stations, and a large decrease in the Dst index that is currently compiled from the records from four selected stations [4].

All regions of geospace are affected by geomagnetic disturbances, and the operations of various technological systems can be impaired or even totally disrupted. For example, during large geomagnetic disturbances the rapidly changing electric currents in the ionosphere (regions within the moving electrojets as well as at distances from them), largely driven by the precipitation of charged particles from the magnetosphere, cause rapid changes in the magnetic field at Earth's surface. These changing fields in turn can induce enhanced electric currents to flow in the Earth's crust and mantle ("telluric currents"). These currents seek the highest conductivity paths, which are often long, e.g., grounded electric grid systems and communications cables. As another example, the enhanced disturbances in the ionosphere can produce serious scintillations in trans-ionospheric radio-wave propagation, even at GHz frequencies. Scintillation effects can be especially large in the equatorial regions at times (producing convective ionospheric storms, often referred to as sporadic E-events), but can be significant across all latitudes.

The occurrence of geomagnetic storms is well associated with Earth-directed coronal mass ejections (CMEs), which appear in coronagraph images as bright halos around the occulting disk [halo CME, 5]. CMEs are eruptions of the solar magnetic field and plasma into interplanetary space, which occur following a large-scale magnetic rearrangement in the solar atmosphere [6, 7, 8, 9, also see several excellent reviews in Space Science Rev., 2006, DOI: 10.1007/s11214-006-9027-8]. Studies of soft X-ray images of the

solar corona indicate that eruptions are more likely to occur in large magnetic configurations that contain a bright sigmoidal structure [10], which is thought to be related to magnetic flux ropes [11, 12]. Potential magnetic field modelling [13, 14] suggests that the origin of CMEs is determined by the global structure of the solar magnetic field and is related to the helmet streamers that are sensitive to the evolution of active regions and/or filaments.

Depending upon the orientation of the magnetic field in the CME-originating region and the sign of magnetic helicity (twist), the Earth-directed CME may or may not have an intense negative B_z field [15]. Hence, the origin of CMEs, the structure of their source regions and their signatures in the solar wind near the Earth are of fundamental interest in the physics of the Sun, space plasmas, and space-weather research.

This paper is organised as follows. In Section 2 we describe the relationship between CME source regions and interplanetary ejecta. Particular attention is paid to the magnetic structure of a CME, and how it corresponds to that of the associated post eruption arcades (PEAs). Section 3 compares magnetic orientations of halo CMEs, tilt of the main coronal neutral line near the eruption site and the directional parameters of the corresponding magnetic clouds. In Section 4 we briefly summarise the results and discuss their implications.

2. Relationship between magnetic fields of CME source regions and the corresponding interplanetary ejecta

Interplanetary counterparts of CMEs are called interplanetary CMEs (ICMEs) or interplanetary ejecta. The internal structure of an ICME is not trivial and may include an ICME body that is often preceded by a shock. The ICME body, in turn, may be observed as a complex ejection [16] or a magnetic cloud [MC, 17].



Fig. 1. LASCO C2 image of a limb CME that erupted on 12 September 2004. This image represents an event with a distinct three part structure and suggests that, at least some CMEs can be described as a flux rope structures.

While MCs are known to be the cause of the most severe geomagnetic storms [18], interplanetary shocks [19] and co-rotating interaction regions [9] are also quite geoeffective, although the storm associated with them are, on average, less intense than those associated with the MCs.

For a number of years researchers have been trying to establish a relationship between CMEs, their complex progenitors, and interplanetary ejecta [20]. Since complex ejecta represent unorganized and compound magnetic structures they were not subject of these studies. Instead, effort was focused on MCs that generally exhibit a magnetically organized geometry, which is thought to correspond globally to a curved flux rope as shown in Figure 1 [also see Figures 1 and 2 in 21, 22, 23] and can be related to various solar parameters such as magnetic field helicity, strength and direction [8]. In particular, significant research efforts have been devoted to finding whether the direction of the magnetic field and the sense of twist found in MCs correspond to those associated with CME source regions (which include both active regions and filaments).

2.1 Association between Ejecta and Post Eruption Arcades

According to various case and statistical studies many interplanetary ejecta maintain nearly the same orientation and twist as the source regions they are associated with [e.g., 12, 15, 22, 24, 25, 26]. This is in agreement with helicity conservation law established for laboratory plasmas. Several statistical studies, however, produced inconclusive results [27, 28]. Harra *et al.* [29] conducted a thorough case study of flaring activity and concluded that the same active region may produce interplanetary ejecta with different magnetic orientations. Therefore, the question about the magnetic connection between interplanetary ejecta

and solar surface phenomena is still open. There are no well defined schemes to predict the magnetic field structure at 1AU based on solar surface measurements present at this moment.

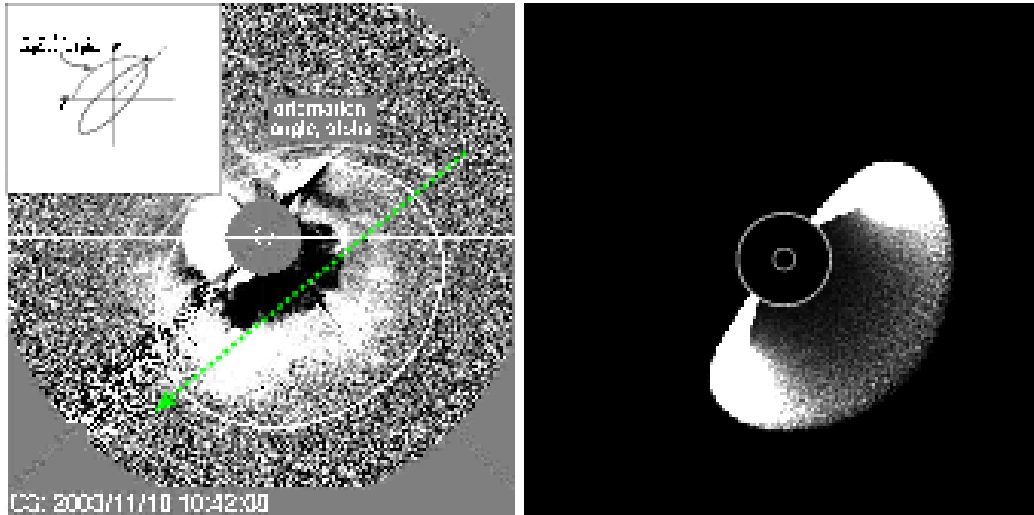


Fig. 2. Left: LASCO C3 difference image for the 2003 November 18 eruption used to measure the CME elongation. The halo CME was measured at its outer edge at intervals of 45 degrees (lines). An ellipse was then fitted to the eight halo points and its tilt angle was determined in the clockwise direction from the y -axis that points eastward to the ellipse semi-major axis (see inset). Right: A synthetic “halo” CME image produced for the same event by the erupting flux rope model. The tilt of the synthetic elongated halo represents the orientation of the simulated flux rope. Comparison with the left panel shows that the tilts of those two halos are similar thus indicating the correspondence between the observed halo elongation and the magnetic axis of a flux rope.

Here, we further explore this problem by utilising magnetic field information measured at various places between the solar surface and the Earth. In particular, we compare directional angles of halo CMEs, heliospheric current sheet (HCS), MCs, and EUV PEA, observed with Extreme Ultraviolet Imaging Telescope [EIT, 30] on board Solar and Heliospheric Observatories [31].

2.1.1. Measurements of CME orientations from white light coronagraph images

White light coronagraph data, such as provided by the Large Angle Spectroscopic CORonagraph LASCO [32] instrument also on board the SOHO spacecraft, show that halo CMEs have various sizes and shapes. Many of them can be enveloped by an ellipse and can be fitted with a cone model [33, 34, 35, 36]. CMEs are also found to be highly structured three-dimensional features [37, 38] and they are thought to represent a flux rope [17, 38, 39, 40, 41, 42]. In particular, Krall & St. Cyr [38] showed that statistical parameters measured for observed CMEs, such as eccentricity and the axial aspect ratio, are in agreement with those obtained for a parameterized model flux rope.

The structured CMEs appear to be magnetically organised in the axial direction, which corresponds to the axis of a large-scale twisted flux rope [37]. At the same time, modelling of erupting flux ropes [43, 44, 45] shows that modelled halo CMEs appear to be elongated in the direction of the axial field of the underlying flux rope. Therefore, it is possible the ellipse-shaped appearance of halo CMEs may be related to their originating magnetic structure.

Yurchyshyn *et al.* [45, hereafter Paper I] studied elongation parameters of 25 halo CMEs and compared them to the corresponding parameters determined for MCs. The CME-MC events were selected from the Master Data Table compiled during a *Living With a Star* Coordinated Data Analysis Workshops [46, 47] and the list published in [48]. All orientation angles were determined in the geo-centric solar ecliptic coordinate system (GSE), where y -axis is in the ecliptic plane pointing towards dusk, x -axis is directed from the Earth towards the Sun and z -axis is pointed northward. The CME orientation angle (or tilt) was determined in Paper I by fitting an ellipse to an irregularly shaped “halo” around the C3 occulting disk (Figure 2) and measuring its tilt in the clockwise direction from the positive GSE y -axis to the ellipse semi-major axis. For each event, we measured the angles in 3-5 images depending upon their availability.

The final tilt angle listed in Table 1 of Paper I was calculated as the mean of angles determined from individual frames.

2.1.2. Orientation of CME elongations versus direction of the axial field in magnetic clouds

The main conclusion drawn from the comparison of CME elongations and MC orientations, discussed above, is that for about 64% of CME-MC events there is a good correspondence between their orientation angles. This supports the idea that the elongation of halo CMEs may indeed reflect the underlying structures of the erupting magnetic fields. If that is the case, these results also imply that the majority of interplanetary ejecta do not significantly change their orientations (less than 45 deg rotation) while traveling from the Sun to the near Earth environment. This was later confirmed by Zhao (2007, private communication). On the other hand, not-so-close-correspondence between CME and MC orientations seems to reflect the existing general confusion about the relationship between solar and MC fields: while for the majority of events magnetic fields at the Sun and 1AU seem to be in agreement, a non-negligible minority of the events display quite different behavior. We note that this correspondence rate may be affected by the fact that some CMEs in the dataset are not full halos. Therefore, their orientations may not be accurately determined.

Another feasible interpretation of these findings was discussed in Yurchyshyn *et al.* [45, 49]: the main axis of a CME may rotate as it expands into the interplanetary space. It could occur as a result of interaction between the ejecta and the heliospheric magnetic field due to coronal viscosity [50, 51]. The rotation may also occur because an erupting twisted flux is subject to kink or torus instability, so that its loop top could rotate as it evolves [52, 53, 54, 55]. Lynch *et al.* [56] and Gibson and Fan [57, also private communication] proposed that an expanding flux rope can reconnect with the surrounding fields and the footpoints of the erupting fields can be displaced, so the erupting flux rope may change its orientation.

The above possibilities will be addressed in the following sections. In order to address the above uncertainties and estimate the reliability of the above findings, a larger statistical study is needed, which would involve more magnetic parameters.

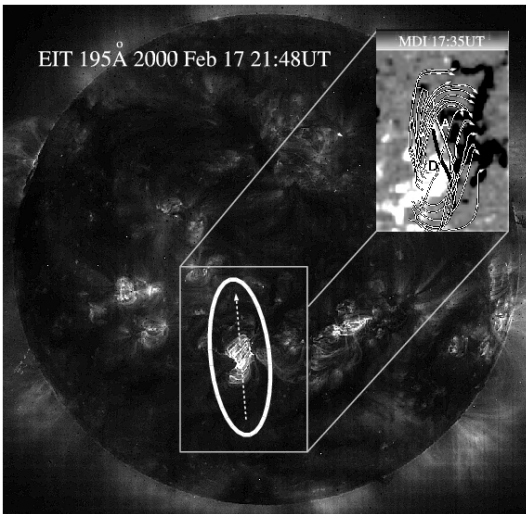


Fig. 3. EIT 195Å image taken on 17 February 2000 at 2148 UT. The flare arcade associated with an eruption is inside the white ellipse that indicates the orientation of the corresponding CME. The white arrow inside the ellipse shows a northwardly directed axial field in the EIT arcade, determined from an Michelson Doppler Imager (MDI, [79]) magnetogram: from positive (white) to negative (black). The “S” shaped arcade indicates a right handed (positive helicity) magnetic structure. The field direction in the corresponding CME was ascribed, based on the EIT arcade and the acute angle method.

2.2. Orientation of CME elongations and direction of the axial field in EIT post eruption arcades

In this section we will compare orientations of Earth-directed CMEs and the corresponding PEAs. Tripathi *et al.* [58] analyzed association between 236 PEAs observed by the EIT instrument and CMEs and found a nearly one to one correspondence between them. Based on this result, PEAs can be considered as reliable tracers of CME events. For each PEA event these authors determined its heliographic position and the length along its axis, which was overlying magnetic polarity inversion lines, when traced back to the Michelson Doppler Imager (MDI, [59]) synoptic charts of the photospheric magnetic field. The heliographic length of the PEAs was found to be in the range of 2 to 40 degrees, with an average of 15 degrees. No error analysis was performed in this study since the primary focus was the range of values and a trend of parameters.

The data set presented in [58] allowed us to determine the tilt (orientation) of these PEAs relative to the solar east-west line. This tilt was measured in degrees in clockwise direction starting from the east. We estimated that in most cases the PEA angles were measured with an

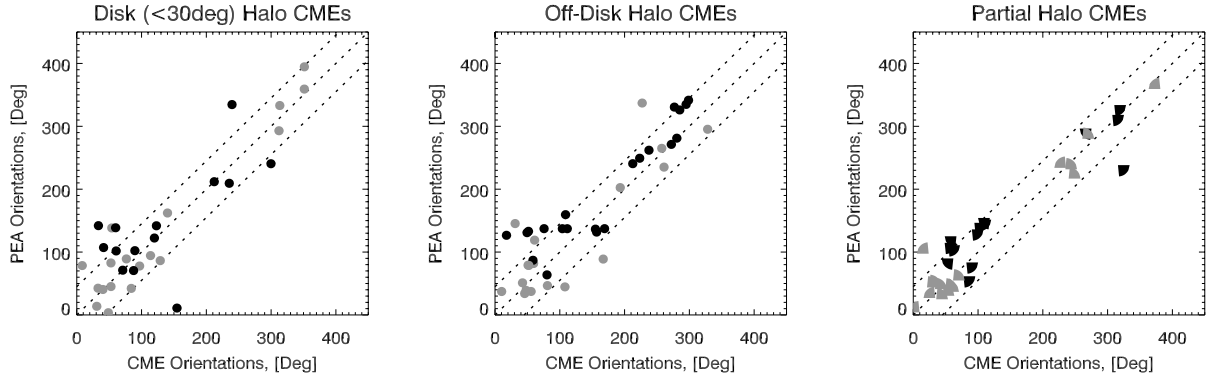


Fig. 4. CME directional angles plotted versus those of PEAs. The panels show (from left to right) data points for disk halo CMEs that originated within a 30 deg circle centered at the disk center, off-disk halo CMEs and partial CMEs. Black (gray) symbols represent events launched from southern (northern) hemisphere. The partial halo events are plotted with pie segments, whose orientation indicates the solar disk quadrant where they originated.

accuracy of ± 10 deg, although in 6 events the absolute error was estimated to be 90 deg.

The list of Tripathi et al. [58] includes various events and not all of them are full and partial halos. For our purposes we needed to modify this list and discard all events associated with narrow and limb CMEs. Therefore, we were left with 101 PEA-CME events. For each full or partial halo CMEs from the list we determined its orientation as described above.

Since a PEA is a magnetic structure with a well defined axial field, we can take into account the PEA's axial field and assign direction to the orientation angles. The axial field and twist (helicity sign) in PEAs can be determined from solar data based on i) direct calculations of the predominant current helicity [60, 61, 62]; ii) force free field modelling [63]; iii) magnetic orientation angles [64]; and iv) visual inspection of the loop pattern seen in chromospheric and coronal images such as S-shaped sigmoids [10, 12] and/or dextral and sinistral filaments [65].

To compare these ambiguity resolved directions of PEAs with CME orientation angles, we need to also assign direction to the CME orientations. To do so we use the magnetic field information inferred from the associated PEA. The CME ambiguity resolution is based on the assumption that the direction of the axial field and twist in a flux rope CME corresponds to those of the EIT/H α flare arcade associated with the eruption (see more details in Figure 3). We will, therefore, assume that the axial field of the PEA makes an acute angle with that of the CME.

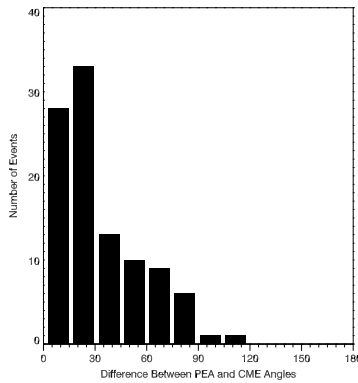


Fig. 5. Distribution of angle difference between CME and PEA orientations. For 74 out of 101 events (73%) the difference is less than 45 deg.

In Figure 4 we plot CME directional angles versus those of PEAs. The panels represent (from left to right) disk halo CMEs, off-disk halo CMEs and partial CMEs. First note that in all three cases the data points are mainly clustered near the bisector. In Figure 5 we show the distribution of PEA-CME difference angles plotted for all events. As it follows from the distribution plot, for the overwhelming majority of events (72%) the difference between the angles is less than 45 deg. It is worth emphasizing here that this holds true for both the partial halos and the halos that originate away from the disk center, where the projection effect is expected to play a significant role.

The data presented in Figures 4 and 5 indicate that, on average, the elongated halos are oriented along the axis of the corresponding PEAs. In addition, the elliptical shape of a halo CME may indeed bear information on the geometry of the underlying flux rope. These results also indicate that 64% correspondence between CME and MC orientations discussed in the previous section seems not to be caused by the projection effect in CME imaging, but is rather a result of CME evolution in the interplanetary space. In the next section we will address the relationship between solar and interplanetary magnetic fields by invoking magnetic field data at 2-3 solar radii above the solar surface.

