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CME Origins and Propagation: Importance of the Polar Perspective

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Synopsis

This paper describes the importance of out-of-ecliptic imaging from a polar or near-polar vantage, to the science of coronal mass ejection origins and propagation. In particular, imaging CMEs from only in or near the ecliptic plane limits understanding of their longitudinal structure and extent, and many other aspects of their formation and propagation including the development and release of the flux ropes that drive the strongest CMEs, and the bidirectional effects between CME propagation and the surrounding corona. Polar-vantage imaging is needed to resolve many current mysteries at the heart of heliophysics. Near-Sun imaging of the magnetic field and coronal EUV emission track interaction between CME onset and the surrounding corona and address outstanding questions of CME formation and early propagation. Coronal and heliospheric polar-vantage imaging is critical to outstanding problems of CME launch, acceleration, evolution, and deflection, which are major sticking points both for solar and heliospheric physics and for the applied science of space weather forecasting.

1 Introduction

Coronal mass ejections (CMEs) have a well documented impact on both the heliosphere and on terrestrial space weather (e.g., Miyoshi & Kataoka, 2005; Schwenn, 2006; Pulkkinen, 2007). The question of how and where they erupt in the first place is critically important to many questions about the Sun itself, from the energetics and magnetic organization of the corona (e.g., Gibson, 2015; Gibson et al., 2018) to the strength of the interplanetary magnetic field (e.g., DeForest et al., 2011); and also drives understanding of space weather.

Further, CMEs are themselves affected by coronal and prior solar wind structure, which are known to profoundly affect interplanetary CME (ICME) propagation via distortion (Howard & DeForest , 2012), deflection and rotation (Isavnin et al., 2014; Kilpua et al., 2017), and CME-CME interactions (Gopalswamy et al., 2001; Lugaz et al., 2017). Even before a CME has left the Sun, long-rang interactions between eruptive events may occur across a complete solar hemisphere (Schrijver & Title, 2011; Titov et al., 2017), indicating the importance of global-scale longitudinal magnetic connections to CME pre-eruption phases and eruption itself.

However, current understanding of three-dimensional structure and evolution of CMEs relies primarily on models, because the relevant structures are, in general, oriented by the Sun's rotational axis and the longitudinal view is inaccessible from the ecliptic plane. While some 3-D information about CMEs is available from stereoscopy (Howard et al., 2008; Liewer et al., 2011; Volpes & Bothmer, 2015), polarized imaging (Howard et al., 2013; DeForest et al., 2017; Mierla et al., 2022), or kinematically constrained tomography (Jackson et al., 2011), these methods are limited by line-of-sight effects and cannot alone fully address the east/west structure of CMEs and their interaction with the corona and heliosphere.

Understanding the role of CMEs thus requires observations from the polar vantage: both on-disk, to capture the magnetic boundary and lower-coronal morphology of relevant coronal structures, and also to track CMEs as they erupt, propagate through the overlying corona, shed magnetic helicity, and interact with the solar wind itself.

In the following sections we describe the importance of polar-viewpoint observations to critical outstanding questions about CMEs and their role for the star and for space weather. Section 2 describes the two-way relationship of high-latitude CMEs and the global magnetic structure of the Sun through the solar cycle, and the difficulties posed by non-polar viewing of these important structures. Section 3 discusses the CME eruption process, how CMEs interact with the existing coronal structure, and the critical need for polar observations of this sequence for both polar CMEs and lower-latitude events including conventional filament eruptions and flare-associated CMEs. Section 4 outlines the interaction between CMEs and the surrounding solar wind medium during propagation, and the urgency of observing CMEs from a polar perspective as they propagate through the inner heliosphere. Section 5 sums up the most critical measurements and their importance to "pure" heliophysics and space weather studies.

2 Polar Magnetic Structures

High-latitude closed magnetic structures provide unique clues to CME origin, manifesting the physical process of storage and release of magnetic energy in "slow motion" on global scales, on time scales of hours or even days leading up to eruption (e.g., Gibson, 2015). In particular, polar crown filaments (PCF), which form near solar minimum at the edge of the

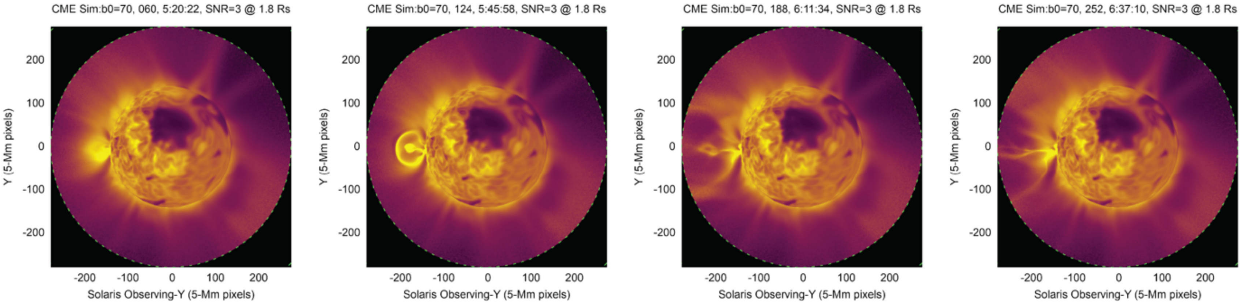

Figure 1: Time-dependent simulation of a CME eruption seen from the polar vantage through a modeled EUV telescope reveals critical aspects of the eruption and its effects on the corona, that cannot be measured without the poalr vantage. The dark central spot is the polar coronal hole. The bright arc at 5 o'clock through 10 o'clock around the pole is an arcae marking the energized cavity above a polar crown filament. An active-region CME erupts at 9 o'clock on the limb, perturbing the corona. Measuring longitudinal extent of these features and disturbances, and their effect on the CME and the global structure of the corona, requires polar observations.

polar coronal holes, accumulate and store magnetic energy and helicity (Gibson et al., 2006) on global scales as the corona evolves near solar minimum (Webb et al., 2011), and have been observed to destabilize over wide longitudinal extents, emitting multiple "unrelated" CMEs simultaneously (Howard & DeForest, 2014). This accumulation of helicity and energy at the PCF is an important aspect of both the solar cycle and the global structure of the corona itself (Mackay et al., 2014).

Understanding the evolution, magnetic content, and morphology of the PCF and its eruptions require longitudinal views of the evolving structure, as illustrated in Figure 1. Because the PCF is always approximately aligned with the plane of the solar equator, separating the PCF spatial variation from temporal evolution on the relevant accumulation time scales of days is difficult or impossible from low latitude vantage points (e.g., Howard & DeForest, 2014), driving a polar approach as illustrated in Figure 1.

3 CME Eruption and Coronal Structure

All CMEs change the magnetic topology and overall morphology of the corona, by opening magnetic field lines (Gosling, 1990), a process that must be counterbalanced by disconnection events (McComas et al., 1992) which are observed both in-situ and remotely (DeForest et al., 2012). Both of these types of event change the magnetic open structure in the corona, and therefore affect the morphology of the corona itself by their passage (e.g., Attrill et al., 2008), thereby also affecting solar wind sourcing (Lörinčík et al., 2021). These morphological changes must occur promptly during the CME eruption itself, and also gradually in the interval between CMEs. While CME passage has known effects which have been extensively observed (e.g., Robbrecht et al., 2009), these observations are necessarily limited to the latitudinal direction by the in-ecliptic vantage point of all coronagraphs to date. As a result, what little is known about the longitudinal structure of the coronal disturbances from CME passage, and their overall effect on the solar wind and heliosphere, arises solely from extrapolation through modeling (e.g., Figure 1).

CMEs seldom erupt radially from the Sun, but rather are deflected by the local mag-

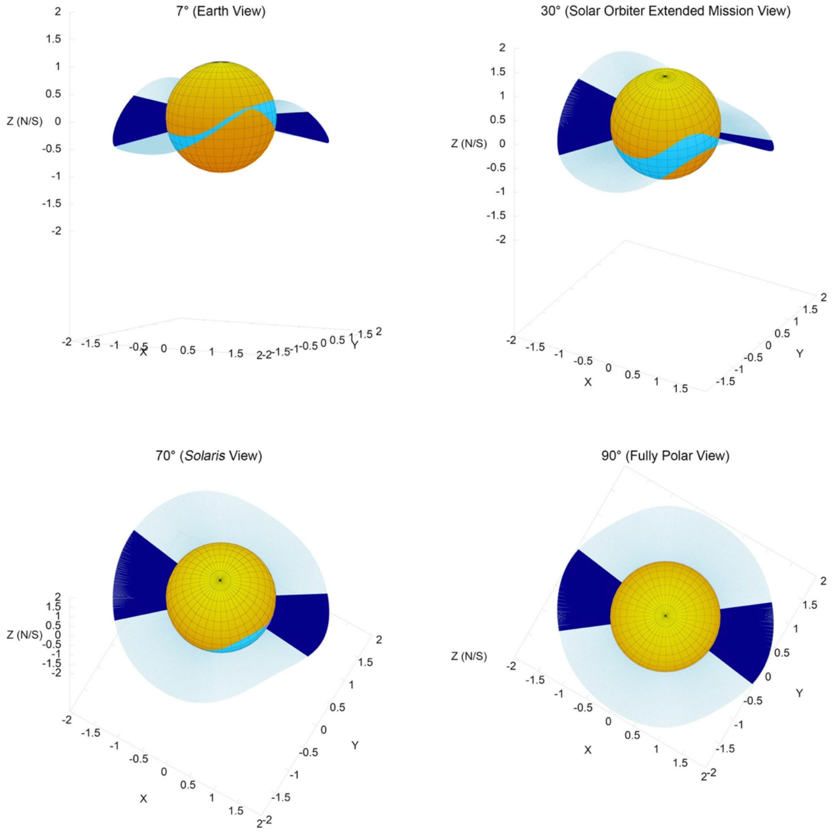

Figure 2: Geometric model of the ”ballerina skirt” of the streamer belt highlights the difficulty of measuring longitudinal structure or CME–streamer-belt interactions without a polar or near-polar perspective. The two dark bands have equal longitudinal extent; their apparent size varies by a factor of order 10 based on viewing geometry. (a) near Earth one dark band is viewed from the ”north side” and one from the ”south side” based on the streamer geometry. (b) slightly elevated perspective (e.g. Solar Orbiter) reveals 3-D structure but strongly foreshortens one side of the streamer belt, reminiscent of the ”quiet sun” corona viewed through SOHO/LASCO. (c) & (d): only near-polar and polar views reveal the longitudinal structure without strong perspective effects.

netic field at the point of eruption. This deflection is often measured in the north/south direction (e.g., Robbrecht et al., 2009; DeForest et al., 2013). Because coronagraphs only measure off the limb of the Sun, this early deflection is not generally visible for halo CMEs. Conversely, the east/west direction of early limb-CME deflection is practically unmeasurable from the plane of the ecliptic, despite the fact that the CME is in principle visible during this early phase of its eruption. As a result, east/west CME deflection in the low and middle corona (Seaton et al., 2022) is neither well measured nor well modeled, confounding both understanding of coronal morphology and space weather forecasting.

CMEs are known to interact with the streamer belt, which modulates the direction and speed of release of both low-latitude and high-latitude CMEs (Manchester et al., 2017; Seaton et al., 2021). A confounding variable in understanding this interaction is that, from current vantage points, the streamer belt is never seen with a truly longitudinal view (Figure 2a). Moderate-latitude out-of-ecliptic viewpoints (Figure 2b) do not solve the problem, because the streamer belt is merely distorted by perspective. Only polar or near-polar vantages separate the north/south aspects of streamer belt interaction and allow measurements of the east/west character of CME release (Figure 2c).

On long time scales of up to several solar rotations, active longitudes form “nesting grounds” for CMEs as new magnetic flux erupts from below the surface, and can persist for months (Gaizauskas et al., 1983; Castenmiller et al., 1986). The time evolution of EUV bright points, obtained by combining Earth and STEREO observations, hint at a Rossby-wave origin of these “nests” (McIntosh et al., 2017; Dikpati & McIntosh, 2019). These active longitudes both form natural semi-repeatable ”experimental workbenches” for understanding the variability of coronal response to CMEs, and also understanding how CME eruption and coronal deflection may be affected by small changes in the local magnetic morphology. These natural experiments are spoiled, from ecliptic or low-latitude vantages, by two inconvenient facts of low-latitude observing: (a) the solar rotation confounds measurements of local morphology as the perspective changes; and (b) the low-latitude viewpoint confounds measurement of latitudinal deflection. Only a polar viewpoint allows invariant perspective on these long-lived regions, permitting semi-controlled experiments as multiple CMEs arise from the same magnetic system.

4 CME Propagation in the Inner Heliosphere

CMEs are known to evolve and interact with the surrounding medium as they propagate outward through the inner heliosphere. Current observations generally support a model of CMEs as magnetic flux ropes (Gosling et al., 1987; Lepping et al., 1990) modified by pickup of coronal and solar wind structures via the “snowplow effect” (DeForest et al., 2013). However, magnetic structures change during propagation from distortion (**?**), deflection and rotation (Isavnin et al., 2014), CME-CME interactions (Gopalswamy et al., 2001), magnetic reconnection/erosion (Gosling et al., 2005; Ruffenach et al., 2015), and other effects (Figure 3 LEFT). CME structure is observed to be extremely complex in the image plane as seen from STEREO (Figure 3 RIGHT), and even 3-D observations via stereoscopy (STEREO) or polarization (the in-development PUNCH) cannot fully capture detailed structure along the line of sight to match the observed complexity in the perpendicular plane. Because of the typical east-west structuring of active-region magnetic fields and polar crown flux ropes, CME structure is likely anisoropic and therefore full understanding of CME eruption and propagation requires the polar view to capture the complex interior structure, and its evolution, in the longitudinal direction.

CME deflection during propagation is an outstanding mystery of space weather physics: while it is observed in the outer corona (e.g., Gui et al., 2011)) and possibly the inner heliosphere (Shen et al., 2022), the energetics of the CME outweigh those of the surrounding magnetic field and solar wind, so that even magnetic draping effects “should” have minimal impact on trajectory (e.g., Gosling & McComas, 1987). In-ecliptic views of propagating CMEs are available from STEREO (**?**), but in these views the CME itself obscures any visible reaction from the surrounding material, limiting image analysis; and in-situ measurements do not sample the material around the CME well enough to capture the subtle effects of Newtonian dynamics and determine whether observed effects such as erosion/reconnection enroute (Gosling et al., 2005) can account for the observed deflection. Only a near-polar situated wide field heliospheric imager, capable of tracking CMEs through the inner solar system, can resolve (a) whether observed deflections far from the Sun are due to perspective

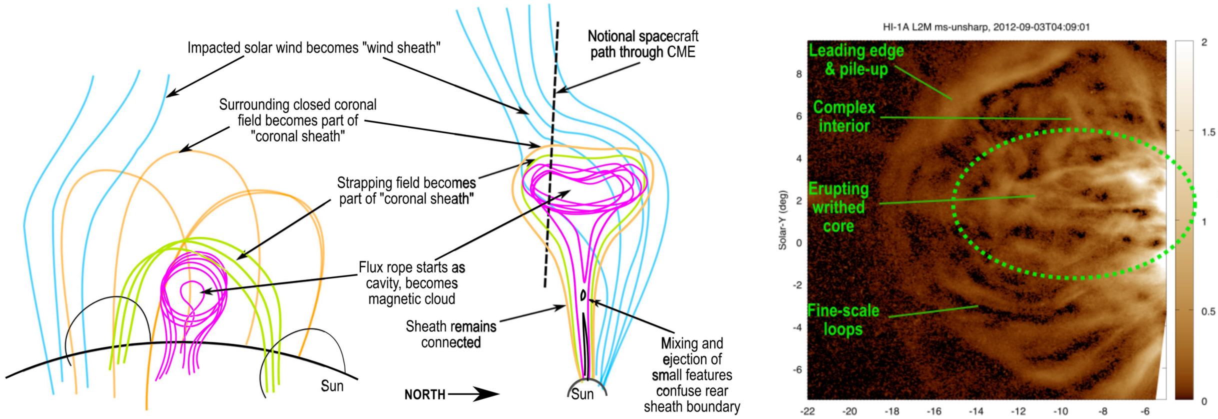

Figure 3: LEFT: Complex structure of a CME is represented in this cartoon developed from direct tracking of a CME by DeForest et al. (2013), and shows remnants of interaction with the corona and the young solar wind before the CME impacts an in-situ probe near Earth; RIGHT: detailed structure of a CME in the inner heliosphere, imaged with STEREO/HI1, reveals the importance of imaging and tracking structure within the overall CME envelope. Because of the overall anisotropy of CME magnetic structure, understanding CMEs' initial form and interactions en-route requires out-of-plane viewing as they form, erupt, and interact with the corona, the inner heliosphere, and other solar ejecta.

or other systematic effects; or (b) the mechanism of the deflection.

5 Needed Measurements

To advance understanding of CME physics beyond the ”meridional plane”, four fundamental imaging measurements are needed from vantage points at least 70 degrees from the ecliptic:

- **Line-of-sight full-disk photospheric magnetograms** with spatial resolution tighter than 5Mm on the solar surface and sensitivity of order 10G, to capture the evolution of the surface magnetic field in the vicinity of the polar crown filament, and the reaction of the polar coronal hole to release of constraining helicity when the PCF erupts;

- **EUV imaging** with a continuous field of view extending well into the middle corona (to 3 solar-radii from disk; center Seaton et al., 2022), temperature sensitivity in the 1-2 MK range (e.g, the familiar Fe line clusters at 17.1 nm and 19.3 nm) and the chromospheric range (e.g. the He line at 30.4 nm), to capture the evolving structure, energization, and ultimate eruption of both PCF and low-latitude CMEs;

- **Coronagraphic imaging** capable of resolving coronal structure from within the EUV imaging field of view to 15 or more solar radii, to track coronal response to CME eruption and longitudinal deflection of the CME in the corona; and to identify the formation and evolution of interior structure in CMEs as they interact with the corona and streamer belt;

- **Wide-field heliospheric imaging** to 0.5 AU from the Sun, to probe the mechanism for high-altitude CME deflection and its implications for space weather.

6 Conclusions

We have identified several outstanding problems of CME physics, both from an astrophysical/heliophysical standpoint, and from an applied space-weather standpoint, that require polar vantage to resolve. Understanding CME effects on the polar field, the global structure of the corona, and the Sun's need to shed helicity drives high-latitude EUV and magnetographic views of the Sun's polar region. Understanding CME onset, CME-corona interaction, and longitudinal aspects of CMEs, their interior structure, and their interaction with the corona drive wide-field EUV and visible-light imagers to capture eruption and propagation, and the coronal response, out to roughly 15 solar radii. Understanding CME interaction with the Parker spiral, other ejecta, surrounding magnetic fields, and potential deflection mechanisms drives a wide-field heliospheric imager. These measurements are required to more fully understand CMEs, their interaction with the corona and the star itself, and their propagation, and are critical to advance major areas at the center of heliophysics and space weather science.

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