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Abstract

This white paper is driven by the supposition that significantly improving our understanding of CME internal field structure and how it evolves in the inner heliosphere requires developing the capability to measure and map CME fields in transit to 1 AU. From a space weather forecasting perspective, such capabilities are crucial for developing the capacity to forecast B_z at Earth, which is recognized as the most relevant CME parameter for geoeffectiveness, but is one that is currently impossible to forecast. We here discuss potential new field diagnostics to explore, from the low and middle corona where CMEs are birthed, to the interplanetary medium where the fields can be observed by magnetometers on spacecraft, or by radio Faraday rotation observations from current ground-based facilities or hypothetical future space missions.

1 Introduction

Coronal mass ejections (CMEs) are eruptions of coronal material from the Sun into interplanetary space, first characterized using white-light coronagraphic images of the outer solar corona. Coronagraphic imaging is still how CMEs are most commonly detected, catalogued, and studied [Tousey 1973; Gosling et al. 1974; Hundhausen et al. 1984; Howard et al. 1985; Kahler 1987]. Within the past two decades, perhaps the biggest advance in CME remote sensing is the development of heliospheric imagers capable of tracking CMEs well beyond the fields of view of coronagraphs, all the way out to 1 AU in many cases. The first such capability was provided by the Solar Mass Ejection Imager (SMEI) on the Coriolis spacecraft, which operated in Earth orbit during 2003–2011 [Webb et al. 2006; Howard et al. 2013]. Even more sensitive observations are provided by the HI1 and HI2 heliospheric imagers on the twin STEREO spacecraft launched in 2006, one of which (STEREO-A) is still in operation to this day [Lugaz et al. 2012; Möstl et al. 2014; Wood et al. 2017; Harrison et al. 2018]. NASA’s PUNCH mission (to launch in 2025) will expand upon these assets through nested coronagraph and heliospheric imaging, with unprecedented sensitivity and polarimetric capabilities [DeForest et al. 2022].

In white-light coronagraphic or heliospheric imaging, CMEs are detected via Thomson scattering of solar photospheric light by electrons within the transient. The images are therefore most directly diagnosing electron density within the CME. However, although CME density and mass are certainly quantities of interest, it is the magnetic field that is most central to understanding CME structure. Close to the Sun, the solar corona is clearly ordered by magnetic fields, with coronal structure dominated by loops of magnetic field, often anchored in solar active regions with particularly large photospheric fields. Magnetic reconnection is the origin of solar eruptions of various types (e.g., flares). In situ observations of interplanetary CMEs (ICMEs) reveal that they are often characterized by a region of low plasma β and strong, rotating magnetic fields, properties that define an ICME subclass called “magnetic clouds” (MCs) [Burlaga et al. 1981; Marubashi 1986; Burlaga 1988; Lepping et al. 1990; Bothmer & Schwenn 1998]. These observations have led to the flux rope paradigm, in which CMEs are tube-shaped structures permeated by a helical magnetic field, with legs that stretch back to the Sun [Marubashi 1986; Farrugia et al. 1995; Bothmer & Schwenn 1998]. Finally, CMEs are capable of causing geomagnetic storms when they hit Earth, and the quantity most predictive of CME geoeffectiveness is B_z , the component of the field normal to the ecliptic plane. A strong southern-oriented field is more effective at disturbing Earth’s magnetosphere in a way that yields a strong geostorm. Thus, CME magnetic fields are also crucial for space weather forecasting purposes.

With the central importance of the CME magnetic field established, it is therefore possible to argue that the biggest observational obstacle to our efforts to understand CMEs lies in our inability to effectively measure CME fields remotely. There is a need to both measure and track CME fields as the eruptions expand from the corona into the interplanetary medium, interacting with the ambient quiescent solar wind. Some correlation exists between CME internal field strength and other observables such as CME speed and reconnected flux at the Sun [Gopalswamy et al. 2018], but this diagnostic power is very limited. If mass followed field strength, available information from white-light imaging would be sufficient to address the problem, but in situ observations clearly show that this is far from the case. The internal parts of MC CMEs, where fields are often strongest, are where density is actually lowest within the structure.

Scientific understanding of CME internal field structure and how it evolves in the inner heliosphere requires developing the capability to measure and map CME fields in transit to 1 AU. Furthermore, it is also likely that practical B_z predictions at Earth will never be attainable without some means of observationally constraining the CME field while in transit to 1 AU. Thus, we use this white paper to discuss various avenues that might be explored in the years to come to try to measure the magnetic fields of CMEs in transit to 1 AU.

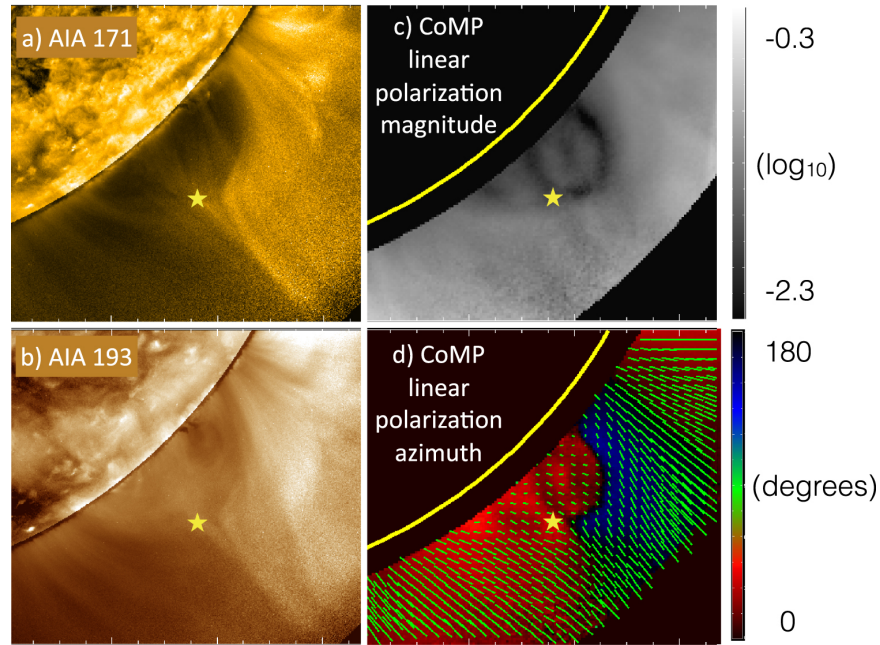


Figure 1: Observations of a pseudostreamer from SDO/AIA and MLSO/CoMP, from 2015 April 18-19. Panels (a) and (b) show AIA images in the 171 Å and 193 Å channels, respectively. Panel (c) shows the CoMP linear polarization magnitude (L/I), and panel (d) displays the azimuth ($0.5 \tan U/Q$). The azimuth direction is indicated by green vectors and by the color scale, with black indicating a radial direction, blue a clockwise tilt, and red a counterclockwise tilt. Yellow stars mark the intersection of the two lobes of the pseudostreamer. The figure is from Gibson et al. [2017].

2 Field Measurements in the Corona

One key question about CME formation lies in the degree to which the magnetic flux rope is a preexisting quiescent structure in the low corona, or whether the flux rope structure is entirely created during the eruption. Ideally, this issue should be addressed observationally by developing the capability to monitor and map coronal magnetic fields within $1 R_{\odot}$ of the solar limb. Observing how the coronal field structure changes from pre-eruption to CME onset could greatly improve our understanding of CME origins. (See Gibson et al. white paper on “Magnetic Diagnostics of CME precursors.”)

An important step toward the remote sensing of coronal fields was the development of the Coronal Multichannel Polarimeter (CoMP), which is integrated into the Mauna Loa Solar Observatory (MLSO) [Tomczyk et al. 2008]. This instrument observed from 2011 to 2018, diagnosing the magnetic field by measuring the polarization of coronal Fe XIII lines at 1074.7 and 1079.8 nm. It has now been replaced by the Upgraded CoMP (UCoMP), which is observing coronal lines at multiple temperatures and for an expanded field of view. However, inferring a unique 3-D field solution from such data is difficult. It can be more practical to use a forward modeling approach to interpret the CoMP data, and tools such as the FORWARD package have been developed to assist in the interpretation of such data [Gibson et al. 2016]. Typical field strengths measured at Sun-center distances of 1.05 – $1.35 R_{\odot}$ are 1 – 4 G [Yang et al. 2020]. An example of how such data can be useful for studying the pre-eruptive states of CMEs concerns a pseudostreamer from 2015 April 18–19, initially observed in quiescence with CoMP [Gibson et al. 2017; Karna et al. 2019], and which is later observed erupting in SDO/AIA and SOHO/LASCO data [Karna et al. 2021]. Images of this pseudostreamer from SDO/AIA and MLSO/CoMP are shown in Figure 1, along with the polarization measurements that lead to inferences about field structure [see Fig. 1 in Karna et al. 2021].

A significant limitation of CoMP is its limited aperture (20 cm), which makes it difficult to regularly measure the circular polarization component (Stokes V). This problem should be resolved within a small field of view ($\sim 5''$) when the Daniel K. Inouye Solar Telescope (DKIST) is fully operational, with its 4 m aperture [Rimmele et al. 2020; Rast et al. 2021]. However, capturing CMEs in eruption almost certainly requires a global field of view, such as planned for the 1.5 m COSMO telescope [Fan et al. 2018]. (See also the white paper on COSMO by Tomczyk et al.) New diagnostic techniques are being developed to utilize the more sensitive observations that DKIST and COSMO can provide [e.g., Dima & Schad 2020; Judge et al. 2021].

Ground-based observatories will always have the limitations imposed by the inability to observe the Sun during nighttime or during inclement weather. This problem is naturally resolved using space-based observatories, preferably located at gravitationally stable locations like the L1 Lagrangian point. The Visible Emission Line Coronagraph (VELC) on board India's first solar space mission Aditya-L1, to be launched later this year, will be the first to try to do spectropolarimetric observations of the Fe XIII 1074.7 nm line from space, providing continuous linear polarization diagnostics of magnetic field direction and topology [Patel et al. 2021]. The proposed 12-cm CLARO instrument would take advantage of the ability to observe the unsaturated Hanle regime in the UV Lyman- α coronal line, yielding another diagnostic of line-of-sight field of sufficient sensitivity to measure field strength in CME precursors, down to a few Gauss. (See the white paper on CLARO by Casini et al.) Such small space-based instruments could potentially be flown to vantage points off the Sun–Earth line. (See, for example, the white paper about the COMPLETE mission concept by Caspi et al.)

3 In situ Field Measurements Using Multiple Spacecraft

Currently, the only way that CME magnetic fields are studied regularly is by using magnetometers on spacecraft that happen to be struck by CMEs, wherever those spacecraft happen to be operating within the heliosphere. These spacecraft include several currently operating near Earth at the L1 Lagrangian point; namely Wind, ACE, and DSCOVR. Also at 1 AU is STEREO-A, with a heliocentric position angle that shifts relative to Earth by about 21.5° per year.

Such spacecraft provide precise measurements of the 3-D fields within CMEs, and these data are responsible for much of what we know about internal CME structure, as discussed in Section 1. The fundamental drawback with such measurements is that a spacecraft provides information only about a single one-dimensional track through the CME. Techniques exist for estimating 3-D field structure from such measurements [e.g., Lepping et al. 1990; Hu & Sonnerup 2002], but these techniques involve many uncertain assumptions. Attempts to confirm these 1-D to 3-D extrapolations using images have yielded mixed results at best. The magnetic flux rope picture is the dominant paradigm for CME structure, with support from both in situ data and imaging, but the flux rope orientations and sizes inferred from imaging and in situ measurements are often very different [Wood et al. 2017]. Complicating things further is the possibility that CMEs might actually consist of multiple flux ropes [Osherovich et al. 1999; Nieves-Chinchilla et al. 2020b; Hu et al. 2021; Wood et al. 2021].

Understanding CME field structure ideally requires the development of observational capabilities beyond those obtainable from a single magnetometer-equipped spacecraft. One obvious path forward is to use multiple spacecraft to probe a single CME. There are already many events that have been observed by multiple spacecraft at different longitudes and/or distances from the Sun. Such studies began with events observed by Helios at about 0.3 AU, which were also observed at 1 AU [e.g., Burlaga et al. 1981]. More recently, radial alignments of 1 AU spacecraft (ACE, Wind, STEREO) with spacecraft operating near planets other than Earth have provided numerous other examples, involving observations from Mercury (e.g., MESSENGER), Venus (e.g., Venus Express), Mars (e.g., MAVEN), and even the outer planets (e.g., Cassini) [e.g.,

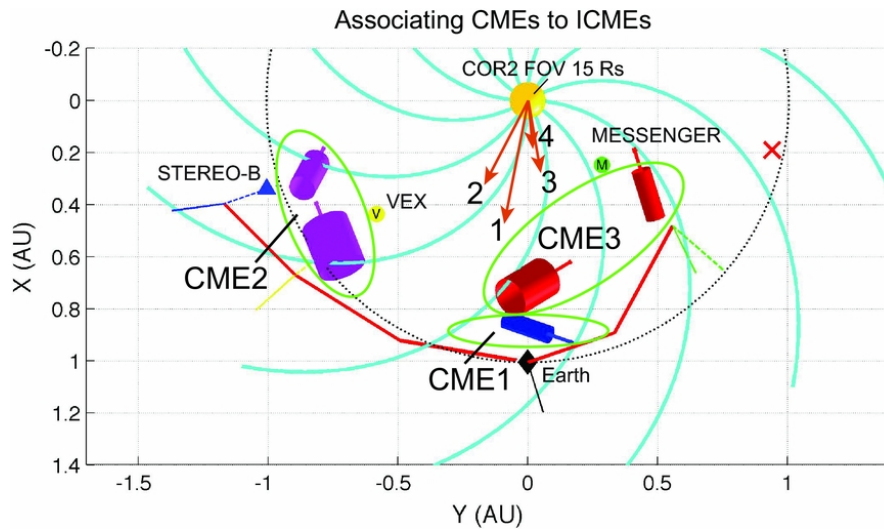


Figure 2: Flux rope orientations (indicated as cylindrical tubes) inferred from multi-spacecraft observations of three CMEs from 2010 August 1. The orange arrows indicate initial CME trajectory directions inferred for four CMEs, based on coronagraph images. Green ellipses encompass observations that are likely of the same CME. CME1 is only observed near Earth, CME2 is seen by both Venus Express and STEREO-B, and CME3 by MESSENGER and near-Earth spacecraft. The figure is from Möstl et al. [2012].

Winslow et al. 2016; Witasse et al. 2017; Lee et al. 2018; Good et al. 2018; Lugaz et al. 2020; Palmerio et al. 2021]. As an example, Figure 2 shows flux rope orientations inferred from multiple spacecraft for three CMEs from 2010 August 1 [Möstl et al. 2012]. Enough multi-spacecraft events have been observed by now that efforts are underway to perform statistical studies based on surveys of multi-spacecraft analyses [Vršnak et al. 2019; Good et al. 2019; Salman et al. 2020; Scolini et al. 2022].

The recent launches of Parker Solar Probe (PSP) and Solar Orbiter (SO) will provide new opportunities for multi-spacecraft studies, with both PSP and SO operating inside 1 AU, and PSP in particular able to potentially encounter CMEs closer to the Sun than ever before. The first multi-spacecraft analyses of CMEs involving PSP and SO have already been published [Winslow et al. 2021; Möstl et al. 2022]. Another valuable opportunity for multi-spacecraft CME studies will be the return of STEREO-A to the Earth’s vicinity in 2022. STEREO-A will approach within 15° of the spacecraft operating near Earth (ACE, Wind, DSCOVR) from 2022 November to 2024 June. While most multi-spacecraft studies of CMEs involve observations at different distances from the Sun, CMEs that hit both STEREO-A and the near-Earth spacecraft will allow analyses to focus solely on longitudinal variation of CME field properties [Lugaz et al. 2022]. Such studies will be able to focus on testing CME structural models, with radial evolution effects being minimized. The STEREO spacecraft were also near Earth shortly after their launch in late 2006, but this was during a solar minimum period of very low activity, meaning there were very few CMEs that were available for study, although there were a few exceptions [Farrugia et al. 2011]. In contrast, the upcoming period of STEREO-A’s near-Earth passage will be near solar maximum, and this should greatly increase the number of multi-spacecraft measurements of CMEs along predominantly longitudinal baselines.

Although near-future multi-spacecraft analyses with existing spacecraft promise significant advances in our understanding of CME field structure and radial evolution, most studies will surely involve a CME probed in only two or perhaps three different locations. This represents a significant improvement of the usual single-spacecraft probe, but still falls well short of being able to reconstruct CME 3-D field structures without significant extrapolation, involving

uncertain assumptions. In the magnetospheric community, there has been an effort to design new missions that probe the magnetosphere in situ with multiple spacecraft, such as the Magnetospheric Multiscale (MMS) mission. Likewise, future improvements in CME research may require missions designed to probe CMEs and other inner heliospheric structures using a fleet of many small spacecraft [Gibson et al. 2018; Nieves-Chinchilla et al. 2020a; Caspi et al. 2022]. A constellation of spacecraft that collectively monitor the Sun–Earth line significantly inside 1 AU is the most obvious path forward to realize a B_z forecasting ability at Earth that is actually useful for practical space weather forecasting. Research should be conducted to explore just how many probes would be necessary to properly characterize a CME’s 3-D field structure [e.g., Al-Haddad et al. 2019; Weiss et al. 2021; Scolini et al. 2022].

4 Radio Faraday Rotation Measurements

The ideal observational diagnostic for CME field structure would be one involving remote sensing, allowing the CME field to be probed from a distance using observations that encompass the full spatial extent of the CME. Currently the only candidate for such a diagnostic is radio Faraday rotation [Kooi et al. 2022]. The Faraday rotation diagnostic relies on detecting the change in polarization position angle (χ) induced by the passage of a CME in front of a background polarized radio source, such as a radio-emitting spacecraft, a pulsar, or an active galaxy. This rotation is

$$\Delta\chi = \left[\left(\frac{e^3}{2\pi m_e^2 c^4} \right) \int_{LOS} n_e \mathbf{B} \cdot d\mathbf{s} \right] \lambda^2 = [RM] \lambda^2, \quad (1)$$

where λ is the observed radio wavelength, and $d\mathbf{s}$ is the differential direction vector along the LOS. The term in square brackets is called the rotation measure (RM), with units of rad m^{-2} .

RM is the integral of the parallel component of the field times the electron density along the line of sight (LOS), multiplied by the constant in parentheses in Equation (1). Thus, modeling RM requires both a field model for the CME and assumptions about its density distribution. Although a single RM measurement at one time only samples one LOS through the CME, if the RM values are measured continuously as the CME passes over the observed LOS, the measured RMs will collectively provide field diagnostics for a 2-D slice through the CME.

There is a long history of using Faraday rotation to study coronal plasma [e.g., Bird et al. 1980; Sakurai & Spangler 1994; Ingleby et al. 2007; Ord et al. 2007; Kooi et al. 2014], but measuring CMEs is harder due to their unpredictable and transient nature. The first serendipitous detections involved radio signals from Pioneer 9 [Levy et al. 1969]. A more systematic effort specifically designed to detect CMEs was made involving radio signals from Helios, resulting in five detections [Bird et al. 1985]. More recently, there has been a study utilizing the signal from the MESSENGER spacecraft [Jensen et al. 2018]. Detections using astrophysical background sources are few. Kooi et al. [2017] reported Very Large Array (VLA) detections of three CMEs on 2012 August 2, and the Low Frequency Array (LOFAR) detected a rotation measure signal even farther from the Sun for an event on 2014 August 13 [Bisi et al. 2016].

Figure 3(a) shows flux rope reconstructions of two CMEs observed by VLA on 2012 August 2, CME-1 to the south and CME-2 to the north [Wood et al. 2020]. CME-2 is observed in situ by STEREO-A four days later on 2012 August 6, making this the only CME ever observed with stereoscopic imaging, radio Faraday rotation, and in situ plasma and field measurements at 1 AU. Wood et al. [2020] describe how this unique combination of observations allows for the reconstruction of the CME’s full 3-D magnetic field structure. Even in the absence of complementary in situ information, the radio measurements can be very useful by themselves for inferring CME field properties, as demonstrated by the CME-1 measurements in Figure 3(b-e).

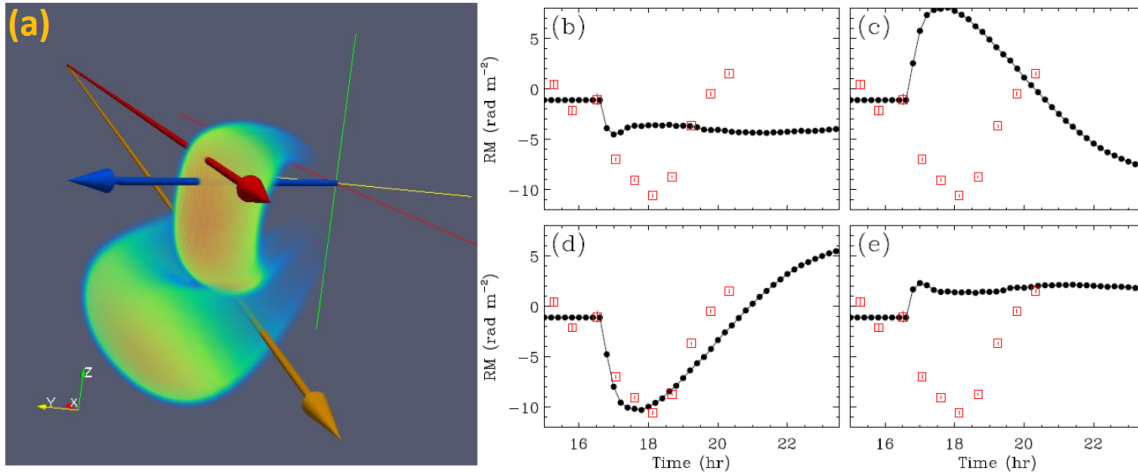


Figure 3: (a) Reconstructed flux rope structures of two CMEs observed on 2012 August 2, shown in HEE coordinates at UT 19:24. CME-1 is the larger, E-W oriented CME, and CME-2 is the smaller N-S oriented event. The blue arrow indicates the direction toward STEREO-A, which goes through CME-2. The red and orange arrows indicate the LOS from Earth toward two background radio sources, 0842+1835 (red) and 0843+1547 (orange), observed by VLA. The 0842 LOS goes through CME-2 and the 0843 LOS samples CME-1. (b-e) The red data points show the VLA RM values of source 0843. The black lines are model RM values assuming the following magnetic field polarities: (b) $(B_t, B_p) = (+, +)$, (c) $(B_t, B_p) = (+, -)$, (d) $(B_t, B_p) = (-, +)$, and (e) $(B_t, B_p) = (-, -)$. The data clearly favor the field polarity assumed in (d). The figure is from Wood et al. [2020].

The VLA RM measurements are compared with four models assuming different internal field polarities. Based on the physical flux rope model of Nieves-Chinchilla et al. [2018], the CME field is essentially defined by two parameters, the axial field at the center of the flux rope, B_t , and the maximum azimuthal field at the surface of the flux rope, B_p . The $(B_t, B_p) = (-, +)$ polarity model in Figure 3(d) is clearly favored by the data, implying that the central axial field of the flux rope is from east to west, and the azimuthal field about the axis is right-handed.

The number of CMEs that have been observed with radio Faraday rotation from ground-based observatories remains very small, which is a consequence of the limited time that observatories like VLA are willing to devote to CME monitoring. Plans are underway for more VLA observing campaigns, in particular ones timed to coincide with PSP close perihelion passages. With solar maximum on the horizon, hopefully these campaigns will significantly increase the number of CMEs with Faraday rotation diagnostics. All the analyses described above rely only on radio observations of a single background source. Obviously, the constraints on the CME field are improved even more if multiple background sources can be monitored behind a CME [Kooi et al. 2021]. An even more ambitious far future vision would be to seek to develop radio observatories sensitive enough to use the radio signal from the Galactic synchrotron background as the radio source [Haverkorn et al. 2000, 2003]. With advances in low frequency imaging arrays (e.g., the Murchison Widefield Array, MWA), it has become possible to image large regions of the sky simultaneously. Developing the capability to use the ubiquitous Galactic background would allow full 2-D rotation measure maps to be made of CMEs propagating in front of that background [Liu et al. 2007; Jensen et al. 2010].

A radio facility devoted to monitoring the Sun for CME Faraday rotation purposes would obviously represent a major advance in developing this capability further. There are also excellent reasons for exploring the possibility of putting such a capability into space. This could, for example, involve a radio transmitter/receiver combination at the L4 and L5 Lagrangian points, which would monitor the Sun–Earth line and measure Faraday rotation signatures for

all Earth-directed CMEs. The FETCH instrument component of the MOST mission concept is an example of such a facility (see FETCH white paper by Jensen et al.). This lateral perspective for Earth-directed events is certainly advantageous for space weather forecasting purposes, with such an observatory potentially providing a path toward operational B_z forecasting. Another advantage of operating from space is that the observations would be free from ionospheric interference, which can complicate the analysis of ground-based data.

5 Summary and Recommendations

The central argument of this white paper is that a focus on future CME research should be on improving our ability to observe CME magnetic fields and monitor their evolution from the Sun and into interplanetary space. The need for improved observational field diagnostics begins in the low corona where the flux rope structures are first formed, and field measurements are needed to explore how preexisting fields are incorporated into the erupting CME. We hope spectropolarimetric coronal observations from DKIST will provide crucial new measurements along these lines. We recommend additional investment in future projects designed to capture CME fields and their precursors, both from the ground (COSMO) and space (CLARO, COMPLETE).

In the near term the bulk of new CME field measurements will come from magnetometers on various spacecraft, as has been the case for decades. Advancing our knowledge about CME field structure along these lines will require improvements in integrating the analyses with available imaging data in novel new ways, and in searching for cases where multiple spacecraft probe the same CME, allowing the combined data to test traditional methods of inferring field structure from single-spacecraft magnetometer measurements. The new PSP and SO missions operating inside 1 AU should provide more opportunities for such research, as will the upcoming conjunction of STEREO-A and Earth. Even more dramatic improvement could potentially be realized in the future if a mission was launched to explore CME structures with multiple spacecraft, analogous to recent magnetospheric missions. Based on model CME flux rope structures, we recommend studies to be performed to explore just how many spacecraft would have to be deployed to adequately probe a CME enough to characterize its field structure.

There is a great need to find some way to measure CME fields via remote sensing. For now, the most promising method is radio Faraday rotation. However, the number of events that have been probed so far is quite small. Efforts should be made to dramatically increase the number of relevant observations so that the promise of this technique can be properly assessed. Such observations can currently only be done from the ground. The possibility of launching a future mission into space devoted to Faraday rotation measurements should be explored (e.g., FETCH), which would involve a very new and exciting way to study CMEs. It should be mentioned at this point that although this white paper focuses on the importance of future magnetic field measurements, realizing the benefits of these measurements will require the continued existence of white-light imaging to provide context for any new field-focused capability, as the imaging data will always provide superior information about large-scale CME morphology and kinematics.

In the context of space weather forecasting, all this research has as its ultimate goal the holy grail of B_z prediction at Earth. Future science-focused multi-spacecraft studies could ultimately provide motivation for a long-term multi-spacecraft mission concept specifically designed to monitor the Sun–Earth line for operational space weather B_z forecasting purposes. Science-driven Faraday rotation studies may be able to demonstrate radio Faraday rotation’s ability to predict B_z . Such studies will need to determine if this is at all feasible from the ground, or if it would require a space-based facility that is both free from ionospheric interference, and can monitor the Sun–Earth line from a more advantageous lateral perspective.

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