3D Polarized Imaging of Coronal Mass Ejections: Chirality of a CME

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Abstract

We report on a direct polarimetric determination of the chirality of a coronal mass ejection (CME), using the physics of Thomson scattering applied to synoptic polarized images from the Solar Terrestrial Relations Observatories/COR2 coronagraph. We confirmed the determination using in situ magnetic field measurements of the same CME with the ACE spacecraft. CME chirality is related to the helicity ejected from the solar corona along with the mass and field entrained in the CME. It is also important to prediction of the space-weather-relevant Z component of the CME magnetic field. Hence, remote measurement of CME chirality is an important step toward both understanding CME physics and predicting geoeffectiveness of individual CMEs. The polarimetric properties of Thomson scattering are well known and can, in principle, be used to measure the 3D structure of imaged objects in the solar corona and inner heliosphere. However, reduction of that principle to practice has been limited by the twin difficulties of background subtraction and the signal-to-noise ratio in coronagraph data. Useful measurements of the 3D structure require relative photometry at a few percent precision level in each linear polarization component of the K corona. This corresponds to a relative photometric precision of order 10^-4 in direct images of the sky before subtraction of the F corona and related signal. Our measurement was enabled by recent developments in signal processing, which enable a better separation of the photometric signal from noise in the synoptic COR2 data. We discuss the relevance of this demonstration measurement to future instrument requirements, and to the future measurements of 3D structures in CMEs and other solar wind features.

Key words: methods: data analysis – polarization – Sun: coronal mass ejections (CMEs) – techniques: image processing – techniques: polarimetric

1. Introduction

The first image of a coronal mass ejection (CME) was taken on 1971 December 14 (Tousey 1973) by the white-light coronagraph on OSO-7. Today, more than 45 years later, the most common images of CMEs are still single-view, total-brightness, white-light images formed from sunlight that is Thomson-scattered by free electrons in the solar corona. These images do not contain any information about the three-dimensional (3D) structure of plasma and embedded magnetic field that comprises the CME; rather, they project the entire structure onto a 2D focal plane.

Although CMEs are flattened in total-brightness images, the polarization properties of Thomson scattering yield information about the 3D location of dense features. The theory of this process has been developed by many authors (e.g., Billings 1966; Howard & Tappin 2009; DeForest et al. 2013). One of the earliest attempts to use polarized white-light images to analyze internal structure of a CME was by Crifo et al. (1983). They used the fractional polarization of a particular CME to indicate the distance from the sky plane of a cleanly presented, circular-appearing CME. They concluded that the CME was a 3D bubble-like structure, rather than planar loop-like structure.

More recently, several researchers have used polarimetric imaging to analyze the large-scale structure and direction of CMEs. In particular, Moran & Davila (2004) used polarimetric imaging to reconstruct the halo CMEs of 1998 October 31 and 1999 June 29 and concluded that these events were expanding arcade loops. Similarly, Dere et al. (2005) used polarimetric imaging to reconstruct the CMEs of 2002 August 1 and 2002 August 7; they concluded that the August 1 event was an expanding loop arcade, whereas the August 7 event was reminiscent of a flux rope. As Dere et al. (2005) conclude, it is clear that polarization measurements can, at least in principle, play a significant role in understanding CME structure and kinematics.

Despite these promising demonstrations, coronagraph polarization data continue to be under-utilized—even after the 2006 October launch of the twin Solar Terrestrial Relations Observatory (STEREO; Kaiser et al. 2008) spacecraft, which regularly record sequences of polarized coronal images. In the STEREO era, some researchers have used polarimetric imaging to reconstruct CMEs as global structures (Mierla et al. 2010; de Koning & Pizzo 2011; Dai et al. 2015). Others have used COR1 images (Moran et al. 2010) and COR2 images (de Koning 2014) to reconstruct some features that are internal to the CME. In all cases, such reconstructions to date have been limited by low signal-to-noise ratio (S/N). In particular, no 3D analyses of small features have been convincingly demonstrated to be above the noise floor.

The limitation of existing 3D location measurement is that interpreting the polarization signal requires approximately an order of magnitude better S/N than does the direct determination of focal-plane structure. Heavy blurring of the original data (via median-filtering or direct convolution with a blurring kernel) have been required in all published cases to beat down photon noise in the coronagraph signal. This blurring has a limited effect on the noise and incurs the penalty of obscuring the detailed structure of the target CME.
In this paper, we apply a recently developed image noise-reduction technique, 3D noise-gating (DeForest 2017), to polarized white-light measurements made by STEREO-A/COR2 during the CME of 2010 April 3. Noise-gating greatly improves the S/N of the images, allowing us to determine directly the structure of small internal features of the CME, including the location and chirality of the central flux rope. Chirality, in particular, is important because it is closely related to the out-of-ecliptic component of the magnetic field (\( B_\perp \)) of the leading portion of the flux rope as it sweeps across the solar system. This leading \( B_\perp \) is a major predictor of geoeffectiveness in Earth-directed CMEs. Measuring chirality of individual CME structures has not been possible with prior analyses, primarily because measuring the 3D shape of CME substructure requires better photometry than has been available at small image scales.

In Section 2, we describe the observations and the noise-gating process, which improves the image S/N. In Section 3, we recap the processing steps to extract the polarized brightness (pB) and total brightness (B) from polarized triplets of COR2 images. We also briefly outline how to determine 3D location from these images. In Section 4, we reveal the extracted structures in the CME; in Section 5, we compare them to in situ traces taken through the same structure by the ACE spacecraft; and in Section 6, we draw conclusions about this initial measurement and discuss their broader implications for heliophysics, for future measurements, and for requirements on future instruments.

2. Data

We analyzed Thomson-scattered images of the mid corona, collected with the COR2 instrument (Howard et al. 2008) on the STEREO-A spacecraft on 2010 April 3. At that time, the COR2 synoptic sequence collected and downlinked a triplet of linearly polarized images of the corona once per hour. The CME was visible in the triplets from (UTC) 10:08, 11:08, and 12:08. For context, we also used coronal images from the LASCO-C2 camera (Brueckner et al. 1995) on board the Solar and Heliospheric Observatory (SOHO; Domingo et al. 1995).

Figure 1 shows the CME, as seen with STEREO-B/COR2, Solar and Heliospheric Observatory (SOHO)/Large Angle and Spectrometric Coronograph Experiment (LASCO)-C2, and STEREO-A/COR2. All three cameras lay in the ecliptic plane, so parallax effects between the images are confined to moving features horizontally. This happy geometric circumstance allows easy cross-identification of features seen by all three cameras, and several are marked in Figure 1. These images have been background-subtracted, as described below.

The horizontal lines “A” and “B” mark two portions of the outer envelope of the CME, as seen from all three instruments. The overall morphology reproduces the “bubble” shape described by Crito et al. (1983). The lines “C” and “D” mark the extent of a central bright structure that is most cleanly seen from STEREO-A and that is highlighted with a dashed box in both the STEREO-A and STEREO-B views. We used polarimetry to characterize not only the outer envelope (the arc tangent to “A” and “B”), but also this small feature that appears to mark the core of the CME.

Historically, photometric and polarimetric analyses of coronal structure have been limited by photon noise because they require percent-level precision in K-coronal brightnesses—which themselves are percent-level perturbations on the F-coronal brightness at moderate apparent solar altitudes of a few solar radii. To reduce the observed noise in the STEREO data, we used the new technique of 3D noise-gating (DeForest 2017). Noise-gating identifies image features that are coherent in space and/or time in an image sequence, and separates them from a parametric photon noise floor, based on the features’ amplitude in the Fourier transform of each image neighborhood. The technique is useful because it selectively preserves statistically significant features in the data based on coherence, and therefore preserves image structure more completely than does direct convolution or neighborhood median-filtering.

STEREO/COR2 data are collected as polarization triplets that can be combined on the ground. We separated the triplets into three independent image streams of Level 1 data (2048 × 2048 pixel images prepared with the STEREO team’s SECCHI_PREP software). We removed bright stars from these images on a per-frame basis using the spikejones unsharp-masking spike detector (DeForest 2004), then used 2 × 2 direct binning to decimate the images to 1024 × 1024 macropixels. We subjected these images to direct noise-gating with 24 × 24 × 12 macropixel (48 × 48 × 12 native camera pixel) neighborhoods and a threshold of 4 times the inferred noise floor, as described by DeForest (2017). Despiking,
binning, and noise-gating together reduced image noise by a factor of more than 30, while preserving image features on the scale of the observed CME structure.

3. Analysis

Thomson-scattered light is polarized by attenuation in the plane of scatter. Therefore the corona appears polarized perpendicular to the radial direction from the Sun, in the focal plane of the instrument (Lytot 1931). The mechanism is projection of the electric field between the planes perpendicular to the incident and departing rays, which arises from the dipolar radiation pattern around the scattering electron (e.g., Jackson 1962). In the context of solar observing, the theory has been published extensively by several authors (e.g., Billings 1966; Howard & Tappin 2009; DeForest et al. 2013). DeForest et al., in particular, include an inversion for determining the out-of-sky-plane angle, \( \xi \), given the degree of polarization.

The brightness from the corona may be imaged directly as brightnesses \( B_R \) and \( B_T \) seen through radially or tangentially aligned linear polarizers, respectively, but is more commonly divided into unpolarized \( B \) and “excess polarized” \( pB \) components, with \( B \equiv B_R + B_T \) and \( pB \equiv B_T - B_R \) (i.e., \( pB \) is just \( \pm Q \) or \( \pm U \) along vertical, horizontal, or diagonal lines respectively, where \( Q \) and \( U \) are the familiar Stokes parameters). The polarization triplets from \textit{STEREO} are collected at polarizer angles of \( 0^\circ \), \( 120^\circ \), and \( 240^\circ \) relative to a reference angle of \( 48.5^\circ \) in the image plane.

We carried out the \( pB \) analysis using direct triplet inversion to recover \( pB \), via the formula

\[
pB = \frac{2}{3} \sum_{n=0}^{2} \left( \frac{1}{2} \right) \cos(2\theta),
\]

where \( B_{120^\circ} \) is the brightness at one polarizer position; all the brightnesses \( pB \), \( B \), and \( B_{120^\circ} \) are functions of focal-plane radius \( b \) and polarizer position angle \( \theta \); and \( \theta \) is relative to the polarizer reference angle. This is the inversion used by the \textit{STEREO} team’s supplied code in the \textit{Solarsoft} system, and arises directly from the observation that

\[
B_\phi = B_R (\cos^2(\theta - \phi)) + B_T (\sin^2(\theta - \phi)),
\]

where \( B_\phi \) is the brightness observed through a polarimeter oriented at the angle \( \phi \), and (as above) \( \theta \) is a polar coordinate in the image plane.

To separate the F corona, instrumental stray light, and prior coronal brightness from the CME, we background-subtracted the despiked, noise-gated images using an ad hoc background model constructed from adjacent-in-time images. In particular, we used the pixelwise minimum of the two prior and two subsequent images from each instrument, as an estimate of all background sources. This commonly used technique is particularly useful for isolating bright CMEs from the relatively steady “background corona,” as well as from the F corona itself.

One problem we found was that the CME itself displaced pre-existing bright structures (ray-like streamer tops) in the corona. This produced dark artifacts in the CME image, as pre-existing bright streamer tops appeared in the background model. We overcame this difficulty by noting that the streamer tops were nearly radial throughout the COR2 FOV. We transformed the background image to radial coordinates and scaled the radial image by a factor of \( r^{2.4} \), where \( r \) is the focal-plane radius of each pixel, to approximately remove the radial brightness gradient. With the radial brightness gradient removed, we identified the average normalized brightness of each column, producing a summary number, \( NB(\theta) \), where \( \theta \) is the position angle around the Sun. \( NB(\theta) \) indicates the relative brightness of each radial line in the original image compared to other radial lines at other position angles. We then multiplied each column in the non-normalized radialized image by a factor of \( NB(\theta) / NB(\theta) \) (where the angle brackets denote radial averaging), and finally transformed the data back to image plane coordinates. This produced a background image in which the radial proportional profiles were preserved, but the azimuthal profiles were approximately equalized. The purpose of the normalizing step is to produce a “typical” correction factor for each radius, rather than allowing the correction factor to be dominated by bright pixels at the innermost radius. The process is illustrated in Figure 2. It yielded a smoother background with the correct radial profile and lacking bright radial artifacts “behind” the CME.

We calculated separate background images for the \( B \) and \( pB \) images of the event, using the same technique for each image type. This produced separate background-subtracted \( B \) and \( pB \) images that were similarly processed and therefore directly comparable for the purpose of ratio analysis. The background identification and subtraction process, in particular, helps to isolate the CME from the background corona. This is important because each of \( B \) and \( pB \) are accumulated along an entire line of sight. Isolating the “feature excess” contribution in the particular feature is important for the direct ratio \( pB/B \), which we use below to infer the 3D location, to be meaningful.

The \( pB/B \) brightness ratio, in particular, yielded surprising structure that is not immediately apparent in either the \( B \) or \( pB \) image. Figure 3 shows three views of the 2010 April 3 CME from \textit{STEREO-A}: \( B \) (unpolarized), \( pB \) (excess tangential polarized), and \( pB/B \) (ratio). The \( pB \) image clearly emphasizes different aspects of the CME from the \( B \) image; but the ratio highlights the 3D structure. It is worth noting that these images are highly smoothed by the noise-gating process; the photometric \( S/N \) in any one COR2 pixel is below unity, and the noise-gating has therefore rejected nearly all small scale information from the image. \( S/N \) on the represented scales in Figure 3 is \( \sim 10–30 \) (depending on location within the image).

The ratio of \( pB/B \) in each bright feature measures the out-of-plane angle \( \xi \) of that feature. In the context of eclipse and coronagraphic analysis, the analytically precise polarization formula is quite complex and is usually evaluated using the qvan de Hulst coefficients (e.g., Billings 1966; Howard & Tappin 2009). At higher altitudes above \(~2 R_\odot\), the Sun may be treated as a point source, and the resulting approximate polarization formula is readily invertible (DeForest et al. 2013) to obtain the location of compact features in closed form:

\[
\xi = \varepsilon \pm \sin \left( \frac{1 - pB/B}{1 + pB/B} \right).
\]
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DeForest et al. (2013). The ± in Equation (3) represents the famous front/back ambiguity relative to the Thomson surface. This ambiguity can be overcome by feature tracking in the wide field (in which the feature’s radial apparent motion ∆e is non-negligible compared to the right-hand side of Equation (3); e.g., DeForest et al. 2013), or by other means of inference in the narrow field or with a single image (e.g., de Koning & Pizzo 2011). We use stereoscopy, noting (in Figure 1) that the core of the CME and the expected point of tangency between the SOHO-observed envelope and the STEREO-A line of sight at the STEREO-A-observed envelope is near or to the right of the SOHO-observed CME centerline. The SOHO-observed CME centerline, in turn, is in the near field, as seen from STEREO-A.

Placing an observed coronal feature in 3D requires converting between the observer-centric coordinate system, in which features are commonly projected onto a focal plane related to angle from the observer, to a Cartesian one. For the coronagraph FOV and moderate precision (~0.25 R⊙) in absolute feature placement, it is sufficient to use the orthographic/Cartesian projection and treat features as if they are projected with parallel rays onto the conventional (x,y) coordinates of the focal plane. Then, the z coordinate (by convention, toward the observer) is just

$$z = \tan \xi \sqrt{x^2 + y^2},$$

where x and y are physical distances in the fictional focal-plane perpendicular to the observer’s line of sight and contain the center of the Sun, and z is a physical distance pointing approximately toward the observer.

We used this orthographic projection to place features in the observer-centric x, y, z coordinate system, then used conventional transforms to convert that frame to the natural-for-stereoscopy heliocentric ecliptic coordinate system, which is defined by an origin at the center of the Sun, +X direction directly toward the Earth, and +Z direction directly toward ecliptic north.

4. Results

Figure 4 shows the 3D structure of key features in the CME, which we derived by extracting the out-of-plane angle ξ at each point in the STEREO-A image. The STEREO-A and SOHO focal planes are rendered at the correct angles. The features are rendered in heliocentric ecliptic Cartesian coordinates. The “STEREO-A view” reveals the portions of the CME that we located in 3D: two oblique elements of the perimeter and the central bright “C” shape. Only these portions are rendered in 3D in the other panels, to avoid confusion effects in the perspective view.

In the SOHO view (left), the central “C” (whose shape is derived from the pB/B ratio shown in Figure 3) corresponds essentially perfectly with a compact, bright feature in the SOHO/LASCO image (encircled with a light green, dashed oval in each panel). The feature is also readily visible in the central panel of Figure 1, but the direct altitude comparison does not show it as unambiguously identical to the “C.”

Figure 5 contains, in the left panel, a close-up of the “C” in the STEREO-A image plane, as seen in standard total brightness, with a parametric curve overlain on the faintly visible “C” itself. The numbers show integrated distance along the curve, in apparent solar radii. The right panel shows the derived out-of-plane distance along the parametric curve.

The error bars in the right panel of Figure 5 are spaced to indicate independent data values after the smoothing that was applied to the data. Their magnitude is calculated based on a posteriori shot noise, using a white noise model and the spatial spectrum of the fully processed data, after noise-gating and subsequent smoothing. Hence, they represent only photometric uncertainty at the focal plane from residual Poisson photon-counting noise, and not uncertainty or error

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introduced by multiple features along the line of sight or by errors in the model background. The error bars are spaced to indicate the approximate distance between independent samples after smoothing.

The small bumps at 0.5 R\(_\odot\) and 1.4 R\(_\odot\) are within a factor of two of the smoothing length in the final images and may be either photometric noise or residual background artifacts. They are probably not significant compared to residual photometric noise. The overall downward trend in the curve is highly significant and represents actual photometric variation at the focal plane. The general trend shows that the out-of-plane position shifts along the length of the marked curve, from approximately 2.8 ± 0.15 R\(_\odot\) out of the plane near the upper portion of the curve to 2.0 ± 0.12 R\(_\odot\) out of the plane near the lower part of the curve.

Because the feature is known from the direct stereoscopy (Figure 2) to be in front of the image plane from STEREO-A’s perspective, rather than behind it, we identify larger out-of-plane distances as closer to STEREO-A. Thus, we conclude that the “C” has a right-handed helical shape, because traversing the near-circular curve in Figure 5 in a clockwise direction causes a displacement into the page. A perfect helix with no measurement noise would yield a smooth diagonal line in the right-hand panel of Figure 4.

This view of the feature as having right-handed chirality is corroborated by the shape of the corresponding feature in the LASCO images. The feature is seen to slant up and rightward in Figures 2 and 4, which agrees with the chiral sense derived from the plot in Figure 5.

The chirality of the CME’s density structure is of interest because it presumably traces the shape of the CME’s internal magnetic field: the CME structure forms deep in the corona where the plasma \(\beta\) parameter is low and density structures are confined by the field. During propagation, those structures are generally preserved, in part because the entire system can become causally disconnected as it propagates outward (e.g., Owens et al. 2017).

The shift in out-of-plane location seen in the right-hand panel of Figure 4 corresponds to a shift in \(pB/B\) ratio in the background-subtracted feature, from approximately 0.76 near the beginning to 0.81 near the end of the identified curve in Figure 5. This represents a differential shift of well under 1% of the raw signal in the Level 0 data.

5. Comparison to in situ Data

The 2010 April event under study has been analyzed by Möstl et al. (2010) and the flank of the CME was found to have hit the Wind and ACE spacecraft (mission descriptions in Acuña et al. 1995 and Stone et al. 1998). In particular, Möstl et al. traced the path of this particular CME through the STEREO-A/HI-1 and HI-2 FOVs. They verified, both from the tracking and from in situ data from the WIND spacecraft, that the northern flank of the CME impacted Earth, ACE, and WIND midway through 2010 April 5.

Möstl et al. discussed at some length the lack of rotating magnetic structure in this CME as measured in situ by WIND, and its implications for magnetic cloud identification and flux-rope modeling. We focus on the cloud portion at the beginning of the ICME ejecta, for which we can determine the chirality since there is a clear magnetic cloud rotation and well-understood propagation geometry.

We examined the magnetic data from the magnetometer on board the ACE spacecraft (ACE/MAG; Smith et al. 1998) and compared it to a cartoon model of a flux rope, to determine whether or not the magnetic chirality agreed with the morphological chirality we found in Section 4.

To illustrate the expected behavior of the magnetic field, Figure 6 shows a cartoon rendering of a generic right-handed flux rope in the familiar Radial, Tangential, Normal (RTN) coordinate system.\(^3\) If the flux rope is considered to be traveling in roughly the +R direction, then an in situ track of the magnetic field at the CME flank taken along the \(R\) direction, in the locus marked with a cyan rectangle, will yield approximately constant magnetic field along the short ±R-aligned chord through the flux rope.

\(^3\) Recall: RTN is a locally Cartesian polar coordinate system. \(R\) is the radial direction from Sun center to an observer; \(T\) is the direction of \(\Omega \times R\) (where \(\Omega\) is the direction of the Sun’s spin pseudovector), and \(N\) points in the third direction (which is close to solar north, for observers close to the ecliptic plane).
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Figure 4. Three different perspective views of the 3D CME of 2010 April 3 11:08 UT show the 3D location of selected features and their position on the SOHO and STEREO-A focal planes, respectively. The STEREO perspective view (right) shows the selected bright edges and the central “knot” of the CME. The oblique view (center) shows the location of the features in 3D. The SOHO view (left) reveals that, as expected, the southern bright “edge” of the CME in the STEREO view coincides with the compressed material at the boundary of the CME at the locus where the STEREO line of sight is tangent to the boundary (the green dashed arc). It also reveals that the compact bright feature corresponds well with the central brightening seen with SOHO (the green ellipse).

Figure 5. CME core seen in unpolarized light (left) is revealed to be right-hand chiral by 3D inversion of the polarization signal on the indicated line (right). The clockwise end of the curve is 0.7 R$_E$ closer to the plane of the sky than the widdershins end. Error bars are derived from the a posteriori statistical properties of the $pB$ and $B$ images (see the text).

Figure 6. Simple cartoon of a right-handed flux rope shows the relationship between chirality and the nearly fixed field direction in the flank of the flux rope. A curved centerline (the red dotted curve) is surrounded by helical field lines (three are shown). The familiar RTN coordinate axes are shown. The shaded rectangle shows a locus near the flank of the flux rope. See the text for discussion.

The direction of this near-constant flank magnetic field is determined by the chirality of the flux rope. As should be clear from the figure, a cut through the northern portion of a right-handed flux rope (whose axis is nearly along the T direction) should yield $T$ and $R$ components with the same sign: either $(+T, +R)$ or $(-T, -R)$. A left-handed flux rope should yield opposite signs for the two components: either $(-T, +R)$ or $(+T, -R)$.

We examined the RTN components of the measured magnetic field from ACE/MAG, together with solar wind data from ACE’s Solar Wind Electron Proton Alpha Monitor (ACE/SWEPAM; McComas et al. 1998), during the flux-rope crossing associated with this CME. Figure 7 shows wind speed ($V_p$), density ($n_p$), alpha-particle abundance ($n_{pp}/n_p$), temperature ($T_p$ and $T_{pB}$), and vector magnetic field ($B_p$, $B_T$, $B_B$) over a 3.5 day interval surrounding the CME encounter, which is marked in yellow. $T_{pB}$ is the expected temperature of the solar wind using a steady-wind heuristic model, and the $T_{pB}/T_p$ ratio, in particular, is useful for highlighting CME plasma (Richardson & Cane 1995). The CME interval marked in Figure 7 is the interval identified by Möstl et al. (2010) on the basis of WIND data, which agrees moderately well with the ACE results. The thermal and magnetic signatures of the CME are clear, though the plasma $\beta$ parametric signature (not shown) is marginal.

Figure 8 shows the evolution of the magnetic field during the passage of the flux-rope flank. During the interval 2010 April 5 12:00–17:00, the magnetic field pointed in the $(+R, +T, +N)$ direction. The field rotated moderately smoothly to the $(R, N)$ plane over the ~16 hr of the interval identified by Möstl et al., finishing in the $(-R, -N)$ direction.

This behavior does not follow the simple progression expected from the geometry in Figure 4: approximately constant $B_T$ and varying $B_R$, with $B_N$ smoothly changing sign. This discrepancy can be explained via a slight rotation of the flux rope compared to Figure 4.

From Figures 1–3, it is clear that the flux rope is propagating approximately 40° below the plane of the ecliptic. The
flux-rope axis is also not aligned directly transversely. Applying a rotation of 40° about the N axis to transform T to T′ and then a rotation of 40° about T′ to yield R′T′N′ coordinates yields a better match to the expected field evolution. Panels (C) and (D) of Figure 8 reveal the magnetic evolution in these modified R′T′N′ coordinates and show the expected qualitative behavior of the field. They are also consistent with a glancing chord through the N′ side of a right-handed helical flux rope with centerline approximately in the T′ direction.

6. Discussion and Conclusions

We have identified the chirality of a bright CME core using the ratio of coronagraphic pB/B from the vantage point of STEREO-A and additional large-scale structural clues afforded by simple stereoscopy. This amounts to a differential measurement of the pB/B ratio with precision of the order of a few percent, after background subtraction, in each resolution element (~4 arcmin) of a smoothed and de-noised coronal image.

Our determination of morphological chirality via polarized imaging is consistent with the inferred chirality of the same structure, as detected in situ by ACE during a glancing chordal passage through the CME. The ACE determination of right-handed chiral structure provides independent validation of the polarimetric measurement.

Chirality measurement is an important first step toward determining the magnetic field direction in CMEs: chirality relates the strength and direction of the magnetic field in the corona to the observed photospheric field. We verified that the morphological chirality we measured agrees with the magnetic chirality of the same event, determined via in situ sampling, as the CME swept over the Wind spacecraft.

Our chirality determination is affected by the famous front/back ambiguity of pB/B measurements; this ambiguity must be resolved in any similar measurement. In the coronagraphic FOV, the Thomson surface is effectively a plane, and the front/back ambiguity requires an external-to-the-instrument measurement (such as stereoscopy). In sufficiently wide-field instruments (FOV wider than ~30°), the front/back symmetry is broken by the spherical shape of the Thomson surface (e.g., DeForest et al. 2013).

Our out-of-plane measurement of the CME core was noise-limited by the characteristics of the COR2 instrument and its observing program. The photon-counting shot noise in the instrument limits the delicate photometry needed for pB/B ratio determination (and is only partially mitigated by the noise-gating process we applied). Further, the 1 hr cadence, which is limited by the telemetry characteristics of the STEREO mission and is also tuned for the primary goal of large-scale CME tracking, prevented a meaningful time-domain analysis of the CME interior features, as they both moved and evolved greatly in the 1 hr interval between each set of polarized triplets. Our measurements were also limited by the crude background model we adopted, which is perfectly adequate for 2D tracking, but is barely adequate for delicate pB/B location work.

Similar determinations of helical structure and other substructure from a future, freshly designed instrument would be improved by greater signal-to-noise ratio in the images and by higher imaging cadence. For example, COR2 operates with a duty cycle of 0.6%. A similar instrument with a shutter duty cycle of 60% would accumulate 100 times more photons, yielding a tenfold improvement in S/N compared to our measurement. Similarly, more rapid observing cadence (enabled by a higher telemetry rate) would permit both improved background models and analysis of structure evolution.

We note that Equation (3) is a compact-feature formula, which directly applies only for features that are small compared to their distance from the Sun. This is the case for small features within CMEs, or even for the region of tangency between a line of sight and a thin shell around a CME, but not for the CME itself. Our demonstration analysis relies on the hypothesis that the CME core was sufficiently compact. As with stereoscopy, truly distributed objects require different techniques that use the polarization images to constrain a geometric model (e.g., Howard et al. 2013).

Our single measurement of 3D substructure within a well-presented CME is a useful demonstration of a hitherto-inaccessible level of precision for the polarization analysis of Thomson-scattered light from CMEs. Such analyses have been limited by the signal-to-noise ratio in existing data sets. This measurement was enabled by a newer post-facto noise-reduction technique (3D noise-gating) that relies on the statistical properties of image noise to separate it from the measurable signal. Future measurements with higher intrinsic signal-to-noise levels will enable more detailed and more common analysis of CME structure than is possible with existing instruments. Such measurements could lead both to better understanding of CMEs and also to a better means of predicting CME geoeffectiveness at Earth (via prediction of Bz direction).
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**Facilities: STEREO** (SECCHI/COR2), **SOHO** (LASCO/C2), **ACE** (SWEPAM, MAG).

**Software:** Perl Data Language; IDL, SolarSoft.

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