

# Tracking CME substructure evolution through the solar wind

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 Sarah E. Gibson, Craig DeForest, Huw Morgan, Curt A. de Koning, Yuhong Fan, Anna V. Malanushenko, Viacheslav G. Merkin, Elena Provornikova, Barbara J. Thompson, David F. Webb  
 National Center for Atmospheric Research, Southwest Research Institute, Aberystwyth University, University of Colorado, Johns Hopkins Applied Research Laboratory, NASA Goddard Space Flight Center, ISR/Boston College

**Abstract**

Future coronagraphs and heliospheric sensors, in particular those to be launched on the PUNCH mission, will have the capability to track the evolution of CME substructures as it evolves through and interacts with the solar wind. The primary motivation being polarimetric data obtained from forward scattering simulations of CMEs in the corona and inner heliosphere. We use these data to track the evolution of CME flux rope dimensions and consider the diagnostic potential of polarimetric data. We find this method

DPS

**Using polarization to deduce 3D position**

DPS

**Distinguishing CME direction**

Neutral measurements in the coronal field between Earth towards and Earth away

**Case 1 Earthwards**      **View from Earth**      **View from Sun**

DPS

**Analyzing flux rope chirality**

DPS

**Conclusions**

- The 3D position of the CME front is well captured using polarimetric analysis for small interplanetary
- Analysis gets more complex for higher interplanetary magnetic field since multiple ionospheric signatures along the line of sight with differing geometries to the Thomson surface.
- Antiquity of rotation from in situ observations apply can be dealt with by observing time series.

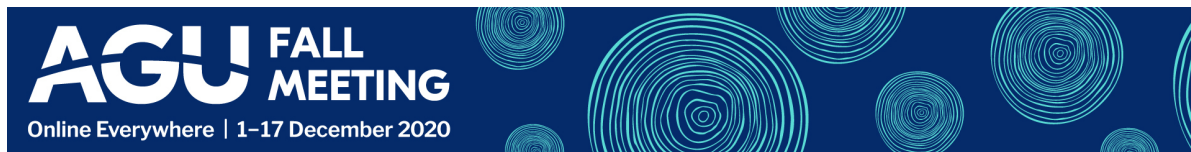
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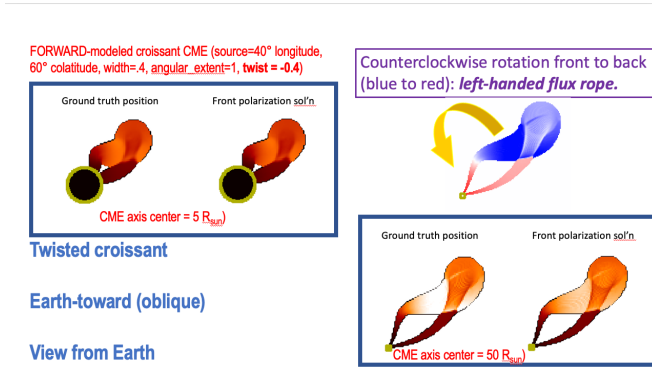
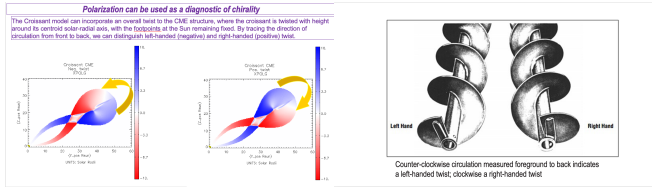
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## ABSTRACT

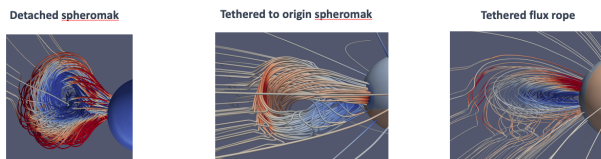
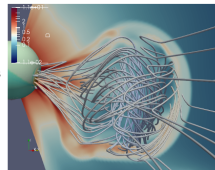
Future coronagraphs and heliospheric imagers, in particular those to be launched on the PUNCH mission, will have the capability to track the evolution of CME substructures as it moves through and interacts with the solar wind. We present analyses using polarization data obtained from forward modeling simulations of CMEs in the corona and inner heliosphere. We use these data to track the evolution of CMEs in three dimensions and consider the diagnostic potential of polarization data. We find this method reproduces 3D position well for structures at small elongation, whereas higher elongations are more impacted by multiple features along the line of sight. We demonstrate that front-back ambiguities may be resolved by observing time evolution of structures, and explore capabilities for extracting information about the chirality of CME magnetic flux ropes from polarization data.

# ANALYZING FLUX ROPE CHIRALITY

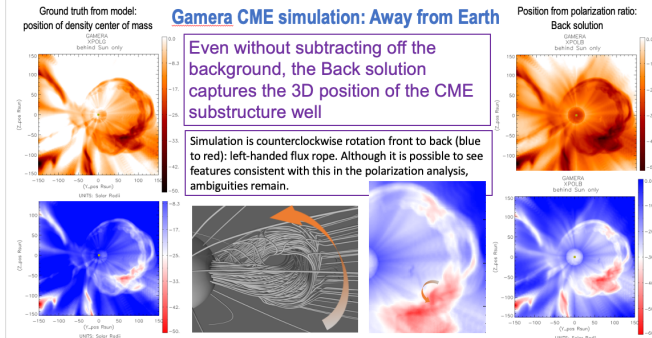


**Polarization diagnostics on MHD model with background solar wind: GAMERA**

- GAMERA is a reinvention of LFM model (Zhang et al. 2019)
- GAMERA-Helio is driven by Wang-Sheeley-Arge (WSA) model of the corona (Wang & Sheeley, 1900; Arge and Pizzo, 2000; WSA model is driven by ADAPT global photospheric magnetic field maps (Arge et al., 2010; Henney et al. 2012)
- GAMERA-Helio-GL incorporates the Gibson & Low (1998) CME, allowing multiple possible topologies (Malanushenko et al. 2020; Provoimikova et al. in preparation)



**Polarization diagnostics on MHD model with background solar wind: GAMERA**



# USING POLARIZATION TO DEDUCE 3D POSITION

**White light polarization ratio can be used to establish position along line of sight**

Light carries an oscillating E-field... which shoves an electron... which re-radiates as a dipole antenna

E-field is reduced by projection:  $\cos^2(\alpha)$

Polarization gives scattering angle  $\alpha$ , elongation angle  $\epsilon$  is observed. Out-of-sky angle is then  $\xi = 90^\circ - \alpha - \epsilon$ . From Law of Sines radial position of object:  $r = (1 \text{ AU}) \sin \epsilon / \sin \alpha$ .

3D position of object: Y, Z from sky-plane projection,  $X = r \cos \theta$ . Ghost solution due to two possible solutions to  $\alpha = \arccos(\text{PR})$ —equally spaced in Front and Back of the Thomson Surface (TS).

Quadrature view

- The polarization ratio  $\text{PR} = B_u/B_v = 1 - F(\alpha) \sin^2 \alpha$
- For a point-source Sun ( $\alpha > 2.3 \text{ R}_s$ ),  $\alpha = \arccos(\text{PR})$
- For lower heights, scattering function  $F(\alpha)$  may be used to deduce  $\alpha$ , e.g., Billings, 1966
- PR can also be expressed in terms of the observed degree of polarization:  $\text{PR} = (1 - \text{p.d.}) / (1 + \text{p.d.})$ , where  $\text{p.d.} = \text{p.d.}$

**Front-back ambiguity about the Thomson surface (TS) may be largely resolved, e.g., if CME source is identified on solar nearside, implying +X trajectory. Time variation can also be used to eliminate Ghost solutions and establish direction of CME.**

Note that Back (CME apex ghost) points can be positive X, but by definition will always be outside the TS

Lines of Sight

Ghost Trajectory (of CME apex)

Trajectory (of CME apex)

Thomson Surface

Quadrature view

Observer

$Z_{\text{pos}} = 140 R_s$

$Z_{\text{pos}} = 50 R_s$

$Z_{\text{pos}} = 5 R_s$

$\xi = 60^\circ$

$\epsilon = 33^\circ$

$\epsilon = 13^\circ$

**Zoom in Quadrature view**

**Assume a croissant type CME (Themisien, 2011; Hutton and Morgan, 2015; 2016) with a trajectory 60° to the Sun-Earth line.**

**Synthesize polarization ratio.** The CROISSANT model has been incorporated into FORWARD Solarsoft package (Gibson et al., 2016)

Lines of sight pass through the near and far sides of the shell of the croissant. The polarization ratio can diagnose the center of mass between these localized structures (DeForest et al., 2017)

CME

**Zoom out Quadrature view**

If CME is earth-directed, LOS-integrated polarization ratio from Front solution accurately reproduces ground truth center-of-mass position in 3D for low elongations.

CME apex at low elongation:  $\epsilon = 13^\circ$

View from Earth

FORWARD-modeled croissant CME (source= $67^\circ$  longitude,  $67^\circ$  latitude, width=1, angular\_extent=4, CME axis center =  $5 R_s$ )

Position from polarization ratio: Back (ghost) solution

Ground truth from model: position of density center of mass

Position from polarization ratio: Front solution

CME apex at mid elongation:  $\epsilon = 13^\circ$

As the structure expands, some of the CME moves outside the TS. For such points, the Front solution becomes the ghost instead of the Back. The Front solution still represents most of the CME.

Back and Front solutions for points at near edge of CME. Points at far edge of CME shift to the back. The Back solution is the correct one.

Back and Front solutions for points at near edge of CME. Points at far edge of CME shift to the back. The Back solution is the correct one.

View from Earth

FORWARD-modeled croissant CME (source= $67^\circ$  longitude,  $67^\circ$  latitude, width=1, angular\_extent=4, CME axis center =  $50 R_s$ )

Position from polarization ratio: Back (ghost) solution

Ground truth from model: position of density center of mass

Position from polarization ratio: Front solution

Interpretation of polarization ratio at CME Top is complicated because LOS intersects both solutions at far edge, and Front solutions at near edge. Points at center and bottom of CME are still represented by Front solutions; their distance is somewhat underestimated because the far edge of the croissant is closer to the TS than the near edge and is 4x weighted more.

CME apex at high elongation:  $\epsilon = 13^\circ$

The entire top part of the CME is now outside the TS, involving the Back solution. The Front solution still approximately represents the ground truth for the points that impact the Earth.

Back solution needed for points at top of CME

Front solution will approximate for most of the CME, including the points that impact the Earth.

View from Earth

FORWARD-modeled croissant CME (source= $67^\circ$  longitude,  $67^\circ$  latitude, width=1, angular\_extent=4, CME axis center =  $100 R_s$ )

Position from polarization ratio: Back solution

Ground truth from model: position of density center of mass

Position from polarization ratio: Front solution

The region LOS intersect both Back and Front solutions. Points at center & bottom will be represented by Front but missed for the edge proximity to TS.

# DISTINGUISHING CME DIRECTION

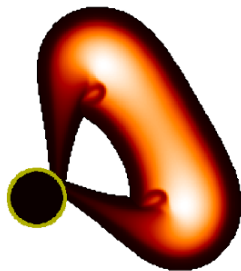
*Polarization measurements vs. time can distinguish between Earth-towards and Earth-away*

## Case 1: Earth-towards

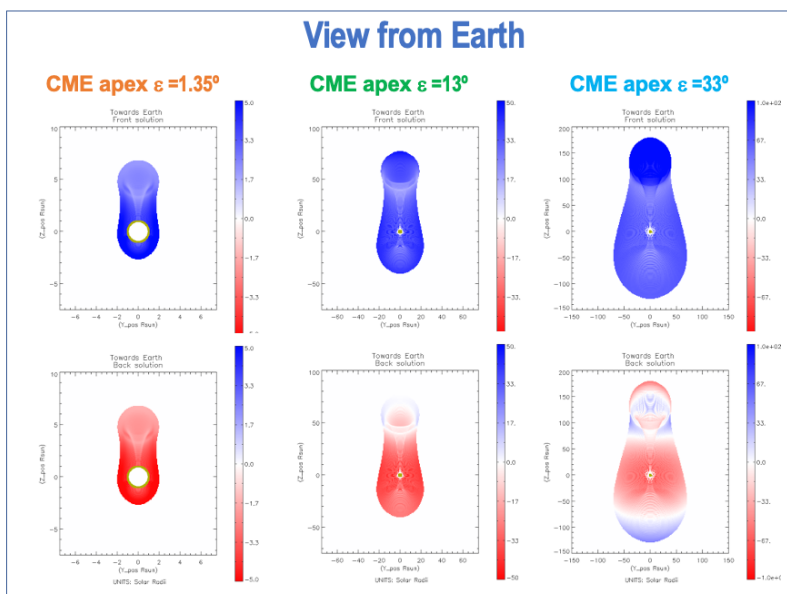
Clues:

- Front solution LOS position stays positive and all points get more positive with time
- Back solution starts negative but parts get more positive with time, ultimately transitioning to positive X (blue)

### Quadrature view



### View from Earth

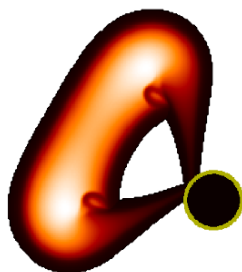


## Case 2: Earth-away

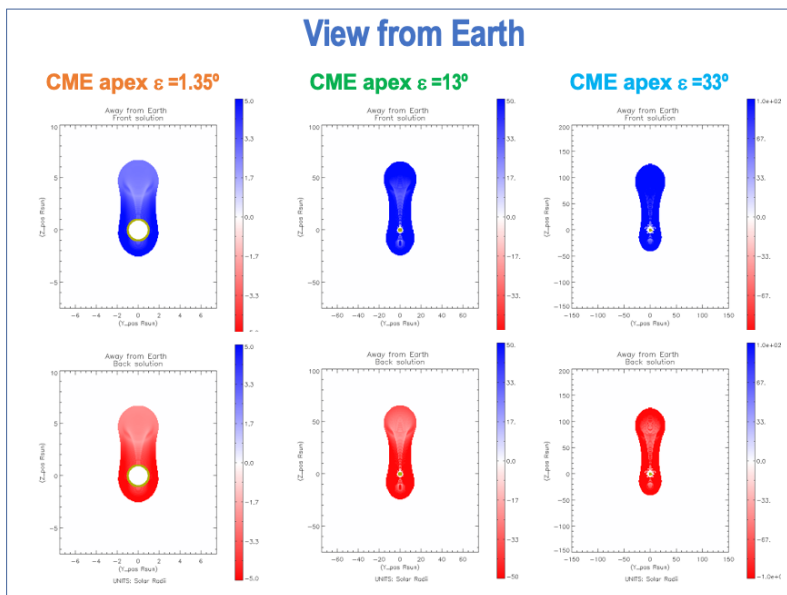
Clues:

- Back solution LOS position stays negative the whole time and all points get more negative with time
- Front solution LOS position stays positive the whole time and all points get more positive with time

### Quadrature view



### View from Earth



## CONCLUSIONS

- The 3D position of the CME front is well captured using polarization analysis for small elongations
- Analysis gets more complex for higher elongations especially if there are multiple localized structures along the line of sight with differing proximities to the Thomson Surface.
- Ambiguity of whether Front vs Back solutions apply can be dealt with by observing time series.
- Polarization presents a tool for distinguishing between left-handed and right-handed CME flux ropes. However, the oblique view (perpendicular to the axis) can be ambiguous. 3D realization of the feature allows rotation to a viewing angle along the axis, ultimately required for establishing chirality.
- Future work: Consider effect of noise

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