Radio Remote Sensing of Coronal Mass Ejections: Implications for Parker Solar Probe and Solar Orbiter

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Abstract

Coronal mass ejections (CMEs) are fast-moving magnetic field structures of enhanced plasma density that play an important role in space weather. The Solar Orbiter and Parker Solar Probe will usher in a new era of in situ measurements, probing CMEs within distances of 60 and 10 solar radii, respectively. At the present, only remote-sensing techniques such as Faraday rotation can probe the plasma structure of CMEs at these distances. Faraday rotation is the change in polarization position angle of linearly polarized radiation as it propagates through a magnetized plasma (e.g. a CME) and is proportional to the path integral of the electron density and line-of-sight magnetic field. In conjunction with white-light coronagraph measurements, Faraday rotation observations have been used in recent years to determine the magnetic field strength of CMEs. We report recent results from simultaneous white-light and radio observations made of a CME in July 2015. We made radio observations using the Karl G. Jansky Very Large Array (VLA) at 1 - 2 GHz frequencies of a set of radio sources through the solar corona at heliocentric distances that ranged between 8 - 23 solar radii. These Faraday rotation observations provide a priori estimates for comparison with future in situ measurements made by the Solar Orbiter and Parker Solar Probe. Similar Faraday rotation observations made simultaneously with observations by the Solar Orbiter and Parker Solar Probe in the future could provide information about the global structure of CMEs sampled by these probes and, therefore, aid in understanding the in situ measurements.

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1. Measuring CME B

Understanding the strength and structure of a CME's magnetic field is critical because it is the dominant factor in determining the CME's geoeffectiveness. Faraday rotation is one of the few diagnostic tools with which to probe **B** and **B** fluctuations within 20 solar radii ($R_\odot$).

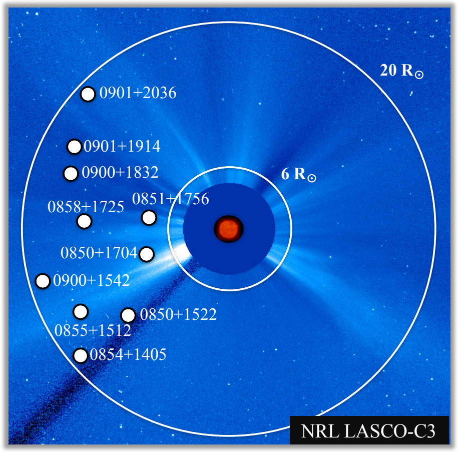

Fig. 1 – Solar corona on July 31, 2015, as observed with the LASCO-C3 coronagraph and SDO AIA 304. The white plotted points are the lines of sight (LOS) to radio sources (identified by J2000 RA & DEC coordinates) at 20:06 UT.

2. Faraday Rotation (FR)

Faraday rotation is the change in the polarization position angle of polarized radiation as it propagates through a magnetized plasma (with density n_e). In cgs, $\Delta\chi$ is given by

$$\Delta\chi = \chi - \chi_0 \equiv \left[C_{FR} \int_{LOS} n_e B_{LOS}\, ds \right] \lambda^2 = \left[RM \right] \lambda^2$$

Here, C_{FR} = 2.631×10^{-17} rad–G^{-1}, B_{LOS} is the magnetic field component along the line of sight in the direction of the observer, and λ is the observational wavelength.

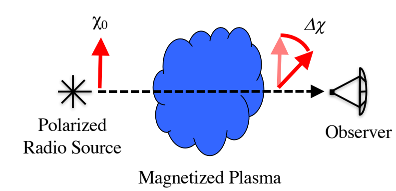

Fig. 2 – Illustration of the LOS from a radio source, through a magnetized plasma (e.g., CME), to a radio telescope on Earth.

3. Thomson-Scattering Brightness (TSB) Compliments FR

Faraday rotation yields a path-integrated measurement of the magnetic field and the plasma density. To separate the contribution of n_e from the B_{LOS} to Faraday rotation, we use Thomson-scattering brightness, B_T, observations from the LASCO-C2 and C3 coronagraphs. B_T depends on assumptions about solar limb darkening and heliocentric distance; beyond 5 solar radii, it is well approximated as

$$B_T \equiv C_T R_0^{-1} \int_{-\pi/2}^{\pi/2} n_e \left(1 + \sin^2\beta\right) d\beta$$

where B_T is in units of solar brightness and C_T = 8.678×10^{-27} cm^3. Total-brightness measurements allow electron densities to be calculated at heights and in conditions inaccessible to polarized-brightness observations. However, the accuracy of deriving n_e from total-brightness observations depends strongly on the accuracy of the removal of the brightness contributions from the F-corona (light scattered off interplanetary dust).

Following Kooi et al. (2017), we assume power law forms for the background coronal n_e and **B**:

$$n_e(r) = N_0 \left(r / R_s\right)^{-\alpha} \qquad \vec{B}(r) = B_0 \left(r / R_s\right)^{-2} \vec{e}_r$$

where r is heliocentric distance and R_s is solar radius. We fit N_0 and α from TSB measurements and determine B_0 from FR when the source was not occulted by a CME. We can then determine the CME's contribution to the observed TSB and FR data by subtracting these fits for the background corona.

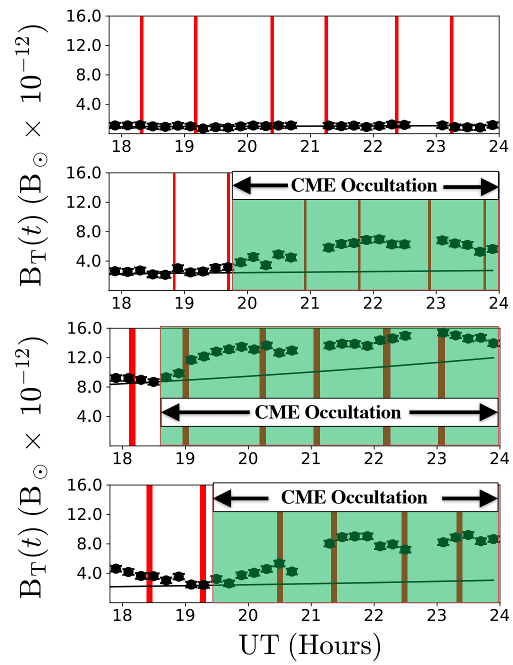

Fig. 3 – Thomson-scattering brightness for radio sources (from top to bottom) 0900+1832, 0850+1522, 0850+1704, and 0851+1756 on July 31, 2015. The TSB is given for one LOS to the target source center. The red bars represent the periods during which the source was observed by the Karl G. Jansky Very Large Array. The CME's plasma density can be determined from the difference between the observed TSB and the fit to the background coronal plasma density (black curve). 0900+1832 (top) was not occulted by the CME.

4. TSB and FR Measurements Enhance Parker Solar Probe and Solar Orbiter

Instruments such as the LASCO-C3 (onboard SOHO) and Karl G. Jansky Very Large Array could track background cosmic radio sources whose lines of sight are occulted by the trajectories of these spacecraft. The resulting TSB and FR measurements could provide information on the global structure of the magnetic fields and the plasma densities sampled by Parker Solar Probe and Solar Orbiter.

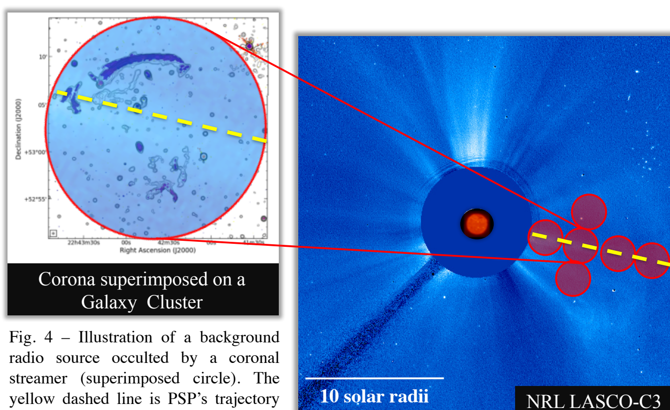

Fig. 4 – Illustration of a background radio source occulted by a coronal streamer (superimposed circle). The yellow dashed line is PSP's trajectory through the corona.

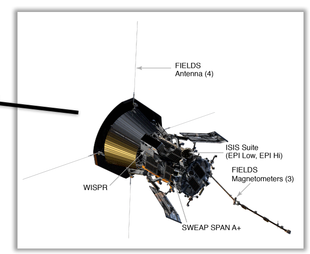

Fig. 4 (cont.) – Ram facing view of PSP as it approaches perihelion, sampling a coronal streamer and, potentially, a CME along its path. The yellow dashed line is PSP's trajectory through the corona as seen by LASCO-C3. The red circles are the fields of view of background radio sources proximate to PSP's trajectory.

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Galaxy cluster image courtesy of Dr. Simona Giacintucci. Image will appear in Di Gennaro et al., in preparation

PSP image courtesy of http://parkersolarprobe.jhuapl.edu/