# Measuring Magnetic Fields of Coronal Mass Ejection in Corona and Inner Heliosphere using Wide Field of View Spectro-polarimetric Radio Imaging


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## Importance of Magnetic Field Measurements of Coronal Mass Ejections (CMEs):

- CMEs are large scale eruptions of magnetised plasma from the Sun.
- Its origin, evolution and geo-effectiveness are determined by its magnetic field.
- CMEs can evolve considerably as they interact with the background solar wind and other CMEs.
- Tracking and measuring their magnetic field from coronal heights to heliospheric distances is essential.
- Routine white-light observations can not provide a direct measurement of magnetic fields of CME plasma.
- Radio observations are well-suited for remote measurements of CME magnetic field remotely.

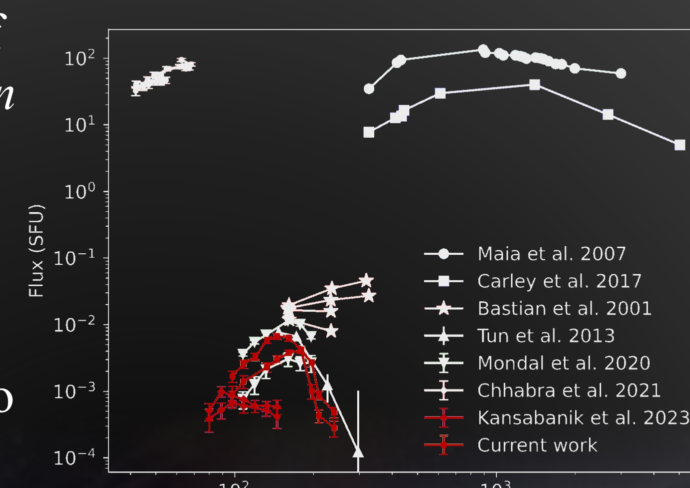
## Techniques at Radio Wavelength for CME Magnetic Field Measurements:

- Direct methods –
  - Radio bursts (upto 1.5 $R_\odot$ using ground-based instruments) – from CME shocks and core.
  - Radio emission from CME plasma (upto ~10 $R_\odot$)
    - Circular polarization of thermal emission (e.g., Ramesh et al. 2020)
    - **Gyrosynchrotron emission (GS)** (e.g., Bastian et al. 2001, Carley et al. 2017, Mondal et al. 2020)
- In-direct methods –
  - **Faraday rotation (FR) measurements** (Kooi et al. 2022, for a review)
    - Using background linearly polarized galactic/extragalactic radio sources
    - Linearly polarized galactic diffuse emission
    - Magnetic field of CMEs have been measured using this technique at coronal heights.

*Spectropolarimetric imaging observation of the GS radio emission from CME is a unique observational tool to estimate CME magnetic fields and other plasma parameters.*

## Challenges and Limitations:

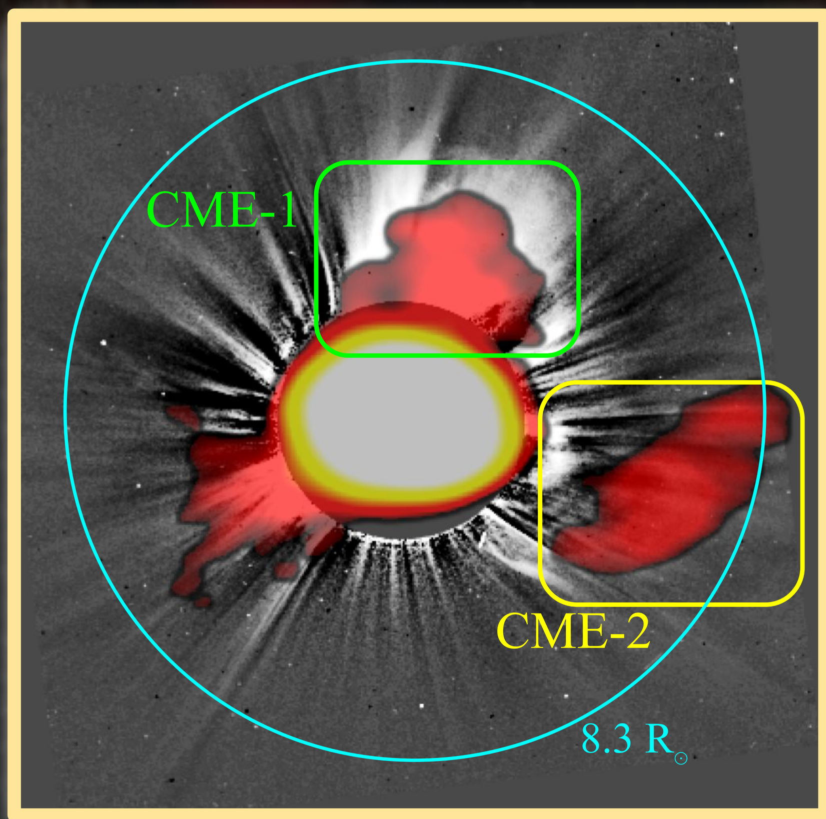
- Limited number of detection *(shown in white)* of faint GS emission from the CME loops due to limited dynamic range of solar radio images produced using traditional instruments.

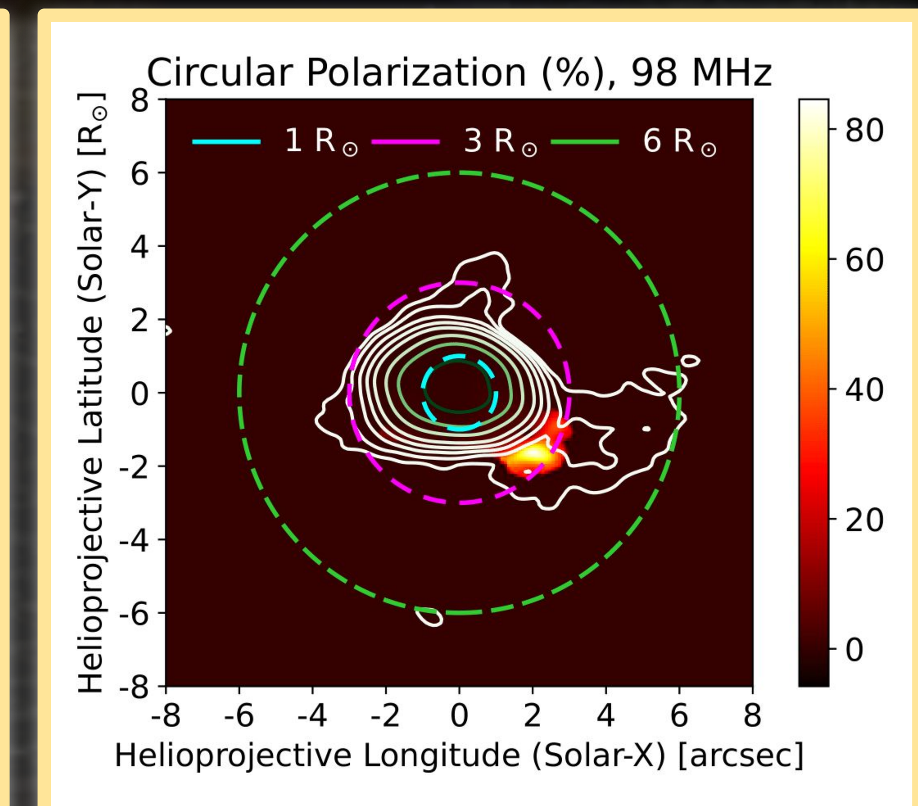



- High dynamic range imaging *(shown in red)* with the new-technology telescope, the *Murchison Widefield Array* (MWA) and state-of-the-art calibration algorithm (P-AIRCARS; Kansabanik et al. 2022, 2023) makes routine spectropolarimetric imaging of CME GS possible.
- Now the challenge is shifted toward modeling the observed emission to robustly estimate the CME plasma parameters.
- Simple homogeneous GS model has ten free parameters – can not be constrained only using Stokes I spectra. Need independent constraints from polarization measurements.

## Spectropolarimetric Detection of GS Emission from CMEs:

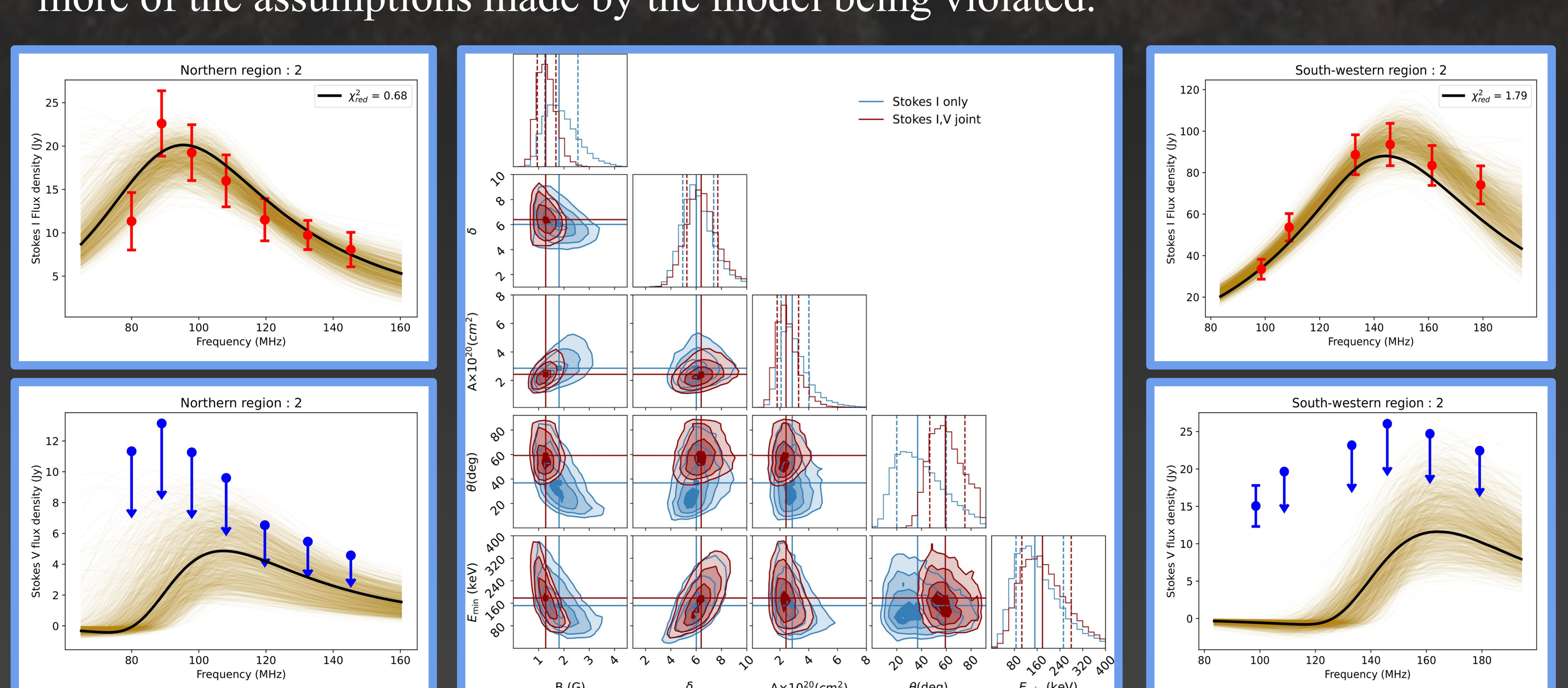
- The adjacent figures shows a CME erupting from the Sun. The grey-shaded image in the left panel is a coronagraph image and the red-yellow superposed image is a radio image made using the MWA observation. The faint GS radio emission is coming from two CMEs (marked by the green and yellow box), denoted by CME-1 and CME-2, respectively.
- These emissions has a brightness temperature of ~5000 K, which is ~200 times fainter than quiet Sun emission.
- The GS emission is detected upto 8.3 $R_\odot$, the largest heliospheric distance to which GS emission has been detected yet..
- Circular polarization image is shown in the right panel. Circular polarization is not detected from CME-1. However, circular polarization is detected from a small part of the CME-2.



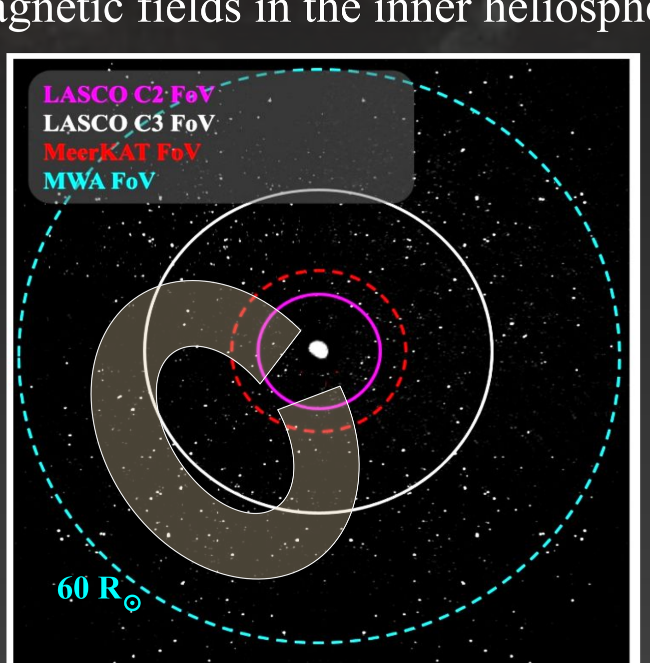

## New insight of GS modeling based on spectropolarimetric observations:

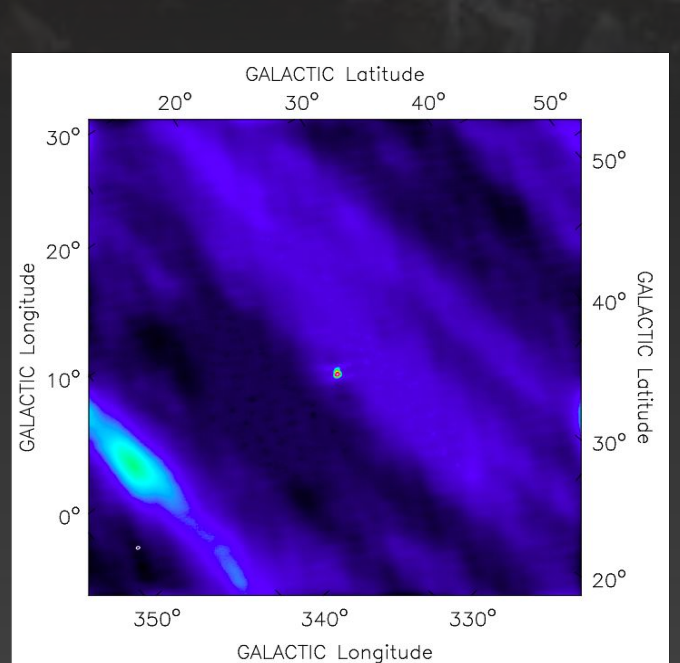
- For the first time both Stokes I and V spectra have been used jointly to constraint parameters of a homogeneous and isotropic GS model.
- For CME-1 (northern CME), no Stokes V is detected. Hence, stringent Stokes V upper limits have been used with Stokes I. Fitted Stokes I and V spectra for a sample region are shown in left panel.
- Inclusion of Stokes V upper limits significantly improves the constraints on GS model parameters, which is evident from compactness of posterior distributions of model parameters shown in the middle panel (Kansabanik et al., 2023).
- For CME-2 (south-western CME), Stokes V emission is detected at a single spectral slice and Stokes I spectra, Stokes V detection and upperlimits have used in modeling.
- A situation like the present, where good model fit can be found for less constraining data, but as the constraints become tighter, it is no longer possible to find a good model fit, strongly suggests the need to critically examine the possibility of one or more of the assumptions made by the model being violated.




## Progress toward CME magnetic field measurements in the inner heliosphere:

- Beyond ~10 $R_\odot$, GS emission can not be used to measure CME magnetic fields.
- In the inner heliosphere, measurement of the changes in the Faraday rotation (FR) of background linearly polarized radio sources (galactic/extragalactic compact sources or the diffuse galactic background) is the only remote technique.
- As linearly polarized emission passes through CME plasma, its plane of polarization rotates depending on the line-of-sight (LoS) magnetic fields and local electron density. Measuring this rotation can provide LoS magnetic fields.
- FR observations have been used to measure CME magnetic fields at coronal heights (Kooi et al. 2017, 2021).
- The MWA is suitable for heliospheric FR-measurements —
  - Wide FoV is required to observe multiple LoS simultaneously, where CME has already expanded.
  - Low-frequencies provide higher sensitivity to FR, enabling us to probe weaker magnetic fields in the inner heliosphere.




***Left panel:*** A hypothetical observation of a CME propagating in the heliosphere. Background image a real MWA Stokes I image with the Sun present at the center. Multiple background sources are seen, some of them are linearly polarized. Linearly polarized sources intersected by the CME plasma can be used to measure the LoS magnetic fields. ***Right panel:*** A MWA image shows the detection of galactic diffuse emission in the presence of the Sun, demonstrating its capability to use it for heliospheric FR measurements (Oberoi et al., 2023).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